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R. Batal

T. Huang

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**COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF HIGHWAYS**



**BUREAU OF MATERIALS, TESTING AND RESEARCH
RESEARCH REPORT**

Research Project No. 66-17

**Prestress Losses in Pretensioned
Concrete Structural Members**

FRITZ ENGINEERING
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**RELAXATION LOSSES IN STRESS-RELIEVED
SPECIAL GRADE PRESTRESSING STRANDS**

by
**Rabih J. Batal
Ti Huang**

**LEHIGH UNIVERSITY
Office of Research**

Fritz Engineering Laboratory Report No. 339.5

Lehigh University

Research Project 339 Reports

**PRESTRESS LOSSES IN PRETENSIONED
CONCRETE STRUCTURAL MEMBERS**

**COMPARATIVE STUDY OF SEVERAL CONCRETES REGARDING THEIR
POTENTIALS FOR CONTRIBUTING TO PRESTRESS LOSSES.**

Rokhsar, A. and Huang, T., F. L. Report 339.1, June 1968

**CONCRETE STRAINS IN PRE-TENSIONED CONCRETE STRUCTURAL
MEMBERS — PRELIMINARY REPORT. Frederickson, D. and Huang, T.,**

F. L. Report 339.3, June 1969

**RELAXATION LOSSES IN 7/16 in. DIAMETER SPECIAL GRADE
PRESTRESSING STRANDS. Schultchen, E. and Huang, T.,**

F. L. Report 339.4, July 1969

**RELAXATION LOSSES IN STRESS-RELIEVED SPECIAL GRADE
PRESTRESSING STRANDS. Batal, R. and Huang, T.,**

F. L. Report 339.5, April 1971

COMMONWEALTH OF PENNSYLVANIA

Department of Transportation

Bureau of Materials, Testing and Research

Leo D. Sandvig - Director

Wade L. Gramling - Research Engineer

Research Project No. 66-17

Prestress Losses in Pretensioned Concrete Structural Members

RELAXATION LOSSES IN STRESS-RELIEVED

SPECIAL GRADE PRESTRESSING STRANDS

by

Rabih J. Batal

and

Ti Huang

This work was sponsored by the Pennsylvania Department of Transportation; U. S. Department of Transportation, Federal Highway Administration; and the Reinforced Concrete Research Council. The opinions, findings, and conclusions expressed in this publication are those of the author, and not necessarily those of the sponsors.

LEHIGH UNIVERSITY

Office of Research

Bethlehem, Pennsylvania

April, 1971

Fritz Engineering Laboratory Report No. 339.5

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ABSTRACT

RELAXATION LOSSES IN STRESS-RELIEVED SPECIAL GRADE PRESTRESSING STRANDS

R. J. Batal and T. Huang

This report contains the preliminary evaluation of relaxation losses based on test data over a period of 444 days. Forty specimens of the seven-wire stress-relieved strands of the special grade (270 K) were tested under a constant length condition. Primary controlled variables are strand size, manufacturer and initial stress level.

Expressions for relaxation loss are developed in terms of time and initial stress. Two sets of expressions are suggested for the estimation of relaxation loss for an initial period up to approximately 500 days. A separate, simplified expression is proposed for long term projection of the total relaxation loss at the end of fifty years.

Also included in this report is a review of previous research on this subject and a summary of the relevant provisions in several foreign as well as United States design codes.

Key words: Computer Programs, Prestressing, Stress
Relaxation, Relaxation Tests

1. INTRODUCTION

1.1 Background

The concept of prestressing is quite old, but its successful application to concrete structures did not start until the late nineteen thirties. Many engineering and economical advantages of prestressed concrete over conventional reinforced concrete were quickly recognized; most importantly, the higher resistance to cracking and deterioration, the more efficient use of materials, and the greater degree of freedom for the designer. These and other advantages accelerated the use of prestressed concrete in many areas of Civil Engineering practice, particularly in the construction of hydraulic tanks and highway bridges. Linear prestressing in the United States lagged behind that of many European countries. It did not begin until 1949, when construction of the famed Philadelphia Walnut Lane Bridge was started.¹³ Since then, the use of prestressed concrete in bridge construction has become very popular in this country. Today, prestressed concrete competes quite successfully with steel as the primary material for highway bridge construction. Pennsylvania leads all the states in the nation in the number of prestressed concrete highway bridges constructed.

In the analysis and design of prestressed concrete structures, a reasonable estimation of the prestress losses is of

the utmost importance. Many factors contribute to the loss of prestress. For pre-tensioned members, the losses due to elastic shortening of the member, shrinkage and creep of concrete, and the relaxation of steel are the four major sources.

While elastic shortening occurs immediately upon releasing of the pre-tensioned strands from their anchorages, shrinkage and creep are long-term, time-dependent phenomena. The loss of liquids due to drying or chemical reactions causes shortening of the member which is known as shrinkage. Creep refers to the continued deformation of concrete due to sustained external loading. Relaxation, on the other hand, represents the decrease of stress in steel under constant strain. This definition, however, is not strictly applicable to a prestressed concrete member, where stress as well as strain tend to decrease.

Considering the four major factors, a general expression may be written for the estimation of prestress losses, as recommended by the ACI-ASCE Joint Committee¹ and AASHTO²

$$\Delta f_s = (\epsilon_s + \epsilon_e + \epsilon_c) E_s + \delta_1 f_i$$

In the above equation, Δf_s represents the loss of prestress, f_i is the initial stress in steel. ϵ_s , ϵ_e , and ϵ_c are strains in concrete due to shrinkage, elastic shortening, and creep respectively, and δ_1 is the percentage loss of steel stress due to relaxation. These recommendations, however, were silent concerning the values of ϵ_e , ϵ_s , ϵ_c and δ_1 . Instead, a lump sum loss

of 35,000 psi was recommended as an acceptable alternative to making detailed estimates of each one of these parameters.

In the Commonwealth of Pennsylvania, the design of the standard pre-tensioned highway bridge member is based on a total loss of prestress of 20% (35,000 psi) for box beams, and 22.8% (40,000 psi) for I-beams. For beams not covered by the standard, the following expression, suggested by the U. S. Bureau of Public Roads,³⁰ (now Federal Highway Administration), is used

$$\Delta f_s = 6000 + 16 f_{cs} + 0.04 f_i$$

where

f_{cs} = initial stress in concrete at the level of
centroid of steel, in psi

f_i = initial stress in steel, in psi

In the above expression, the 6000 represents the effect of shrinkage. The term $16 f_{cs}$ can be split into two parts, $5 f_{cs}$ accounting for the effect of elastic shortening, and $11 f_{cs}$ representing the creep loss. The last term $0.04 f_{si}$ takes care of the relaxation loss. It should be pointed out that the above formula is based on a shrinkage strain of 0.0002, a steel-to-concrete modular ratio of 5, a creep factor of 2.2, and a relaxation loss of 4%.³⁰

It follows that at the present time, the estimation of prestress losses is made either on a lump sum basis, or based on

a few empirical constants like in the Bureau of Public Roads' formula. Neither of the two methods reflects the actual nature of the problem, and both fall short of supplying reliable values of the prestress loss. So, in an effort to establish a more reasonable basis for the prediction of prestress losses in pre-tensioned concrete member, a research project was initiated in 1966, and is presently being conducted, in Fritz Engineering Laboratory at Lehigh University, under the joint sponsorship of the Pennsylvania Department of Transportation and the U. S. Federal Highway Administration.

1.2 Purpose and Objectives

The objective of this research project is to arrive at a rational basis for the prediction of prestress losses in pre-tensioned highway bridge members used in Pennsylvania. Loss expressions are to be established, and prediction formulae will be suggested. For this purpose the major contributions to prestress loss are separated from one another to the extent possible.

The concrete losses (elastic shortening, creep, and shrinkage) are studied in a separate phase of this project. A preliminary investigation compared the overall characteristics of concretes from several prestressing plants. In the main study, two concrete mixes were used and the effects of initial concrete stress, amount of longitudinal steel, and stress gradient were investigated. Expressions for the evaluation of these losses were developed. Details about these studies and preliminary findings

are contained in progress reports No. 1 (May 1968) and No. 2 (July 1969) of this project. Further analysis of additional experimental data will be performed, in order to modify or confirm earlier findings.

The specific objectives of the relaxation investigation, reported herein, are as following:

1. To develop a functional expression for estimating the relaxation loss of prestress during the first two years.
2. To establish a prediction formula which estimates the ultimate relaxation loss over the lifetime of the member.
3. To determine the feasibility of predicting long-term prestress loss from short-time data (100 hours - fourteen days).

2. LITERATURE REVIEW

2.1 Previous Research

The plastic flow of steel under high stress, and conversely its tendency to lose stress when subjected to high strain, has been reported as early as 1834 by Professor Vicat of France.³¹ This fact was quickly forgotten, however, only to be rediscovered upon the engineering acceptance of prestressed concrete almost one hundred years later. With initial tension as high as 175,000 psi, the relaxation of steel became a significant factor influencing the design of a member. Among the first to report about this problem were Redonnet in France²² (1943), and Magnel in Belgium¹⁶ (1944).

Early in 1946 Rös carried out relaxation and creep tests on high strength cold-drawn wires 3.2 mm in diameter. He compared the percentage increase of deformation under constant stress (creep), with the percentage loss of stress under constant length (relaxation). The latter was found to be 50 to 80 percent of the former.

In 1948, Professor Magnel¹⁷ reported the results of his relaxation tests. Cold-drawn wires 5 mm in diameter were tested at an initial stress of 123,000 psi (57% of the tensile strength). The loss in stress occurred mainly during the first few hours, and was completed within a period of twelve days. The total loss was 12 percent. He also reported that the loss decreased to 4 percent,

when a high initial stress of 137,000 psi was introduced and maintained for two minutes before being lowered to 123,000 psi. This was one of the very early reports on the over-tensioning technique for relaxation control.

In England, Clark and Walley⁶ (1953) conducted tests under a constant length condition. Gravitational loads were transmitted through a lever system, to develop the necessary initial stress in the wire. These weights were then reduced as required in order to maintain the constant length. The investigators found that the relaxation ended after 1,000 hours. They also observed that relaxation loss increased with increasing initial stress for levels higher than 40 percent of the 0.1 percent offset stress.

About the same period of time, G. T. Spare published a number of papers^{26, 27} in the United States dealing with the creep and relaxation of high strength wires. His tests demonstrated that stress-relieved wires showed improved relaxation characteristics and suffered less loss as compared to the cold-drawn wires, within the practical range of initial stresses. For stress-relieved material at 70% of tensile ultimate strength some 80 percent of the 1,000 hour loss occurred in the first 100 hours. After 1,000 hours, the rate of relaxation loss became exceedingly small, and could be ignored for practical purposes.

Schwier²⁵ in 1955 confirmed Spare's conclusions concerning the superiority of stress-relieved material for initial

stress up to 75% of the ultimate tensile strength. However, a reversal of this relationship was found at high initial stresses. Papsdorf and Schwier²¹ carried out extensive relaxation and creep tests later, and in 1958 reported their results venturing some long-term projections. The test results showed clearly that the relaxation phenomenon did not stop at 1,000 hours. Extrapolation from their curves to 10^6 (approximately 114 years) indicated very high percentages of stress loss, especially for high initial stresses. [e.g. for an initial stress of 165 kg/mm^2 (230 ksi), 85% of tensile ultimate strength of the 4 mm as-drawn wire used in the test, their curve anticipates a total loss of 21.2% of initial stress.]

Everling⁹ confirmed the conclusions already stated about the relaxation behavior of stress-relieved wires and strands as related to the applied initial stress. He also found that at an initial stress level of 90% ultimate strength, a fast rate of loading resulted in higher relaxation loss. However, the same effect was not observed for stress levels below approximately 80% ultimate strength.

Report No. 14 of C.U.R. (The Dutch Committee of Research), Delft (1958) contained the results of relaxation tests, which also showed that stress-relieved strands demonstrate higher losses at very high ranges of initial stress.

A new technique was used by McLean and Siess¹⁵ for measuring the force in their relaxation specimens. The tensioned wire was electromagnetically excited into forced vibration. From the resonance frequency of the tensioned wire, the actual stress

remaining can be calculated. This method improves greatly the accuracy of measurement.

Dr. Ing. S. Kajfasz¹¹ of Poland performed a number of relaxation tests on single and twin-twisted prestressing wires (1958). Based on a statistical analysis, Kajfasz obtained a number of experimental equations from which he derived the general expression:

$$\Delta f_r = C (\log_e t - \log_e t_o)$$

where:

Δf_r = relaxation in stress units (kg/mm^2)

t_o = time at which first reading was made,
(5 minutes in Kajfasz's tests)

t = time after initial tensioning

C = a parameter depending upon the ratio of initial stress, f_i , to 0.2 percent offset stress, f_y .

Kajfasz suggested a linear relationship for C :

$$C = 2.41 \left(\frac{f_i}{f_y} \right) - 1.395$$

Including the relaxation loss prior to the first reading, Δf_{ro} , Kajfasz's equation takes the following form:

$$\Delta f_r = [2.41 \left(\frac{f_i}{f_y} \right) - 1.395] (\log_e t - \log_e t_o) + \Delta f_{ro}$$

It is interesting to note that for an initial stress level of $0.58 f_y$, $C = 0$ and $\Delta f_r = \Delta f_{ro}$ indicating negligible relaxation loss.

Stüssi²⁸ in 1959 developed a "law of long-term relaxation" using experimental results obtained from relaxation tests performed on cold-drawn wires, 7 mm in diameter and with initial stresses varying from 60 to 75% of the ultimate strength. His study showed clearly, that the higher the initial stress, the higher will be the prestress loss. With remaining stress after relaxation plotted against logarithm of time, it was found that all curves contained a point of inflection beyond which time, the decreasing stress asymptotically approached a common lower limit. Stüssi defined this lower limit as "relaxation limit" (σ_a). For the kind of wires he was using, this limit came out to be 0.53 of the ultimate strength, lying somewhere near the proportional elastic limit at 0.01 percent offset. From a practical point of view, it would not be reasonable to prestress the tensioning steel far beyond this limiting value.

A comment on the foregoing study of Professor Stüssi was released by The Dutch Committee (Betonstaal) in 1960²⁹. The validity of Stüssi's "Relaxation Law" and the material constant σ_a was seriously questioned. The Committee noted that the formula

derived by Stüssi did not agree with a number of earlier relaxation curves. It questioned further the method of extrapolation used by Stüssi, and contended that the value σ_a , even if it were to exist, would have little practical significance.

As part of the AASHO Road Test bridge research program, Kingham, Fisher and Viest conducted one of the very few studies including strands.¹² A total of twenty relaxation specimens were used. Ten of these were 0.192 in. wires, the others were 7-wire strands of 3/8 in. diameter. The duration of their tests varied from 1,000 to 9,000 hours. Three basic requirements underlined their choice of a mathematical model.

1. At time $t = 0$ the stress loss $\Delta f_r = 0$.
2. As time progresses, Δf_r increases at a decreasing rate.
3. Δf_r approaches a finite value Δf_∞ as a limit.

The formula suggested was:

$$\Delta f_r = f_i \left(\frac{f_i}{f_u} \right)^d (1 - e^{-t/a})^b$$

Observing the approximately linear relationship between $\log \Delta f_r$ and $\log t$, the factor $(1 - e^{-t/a})$ was replaced by t/a . Thus the formula was transformed into:

$$\Delta f_r = g f_i \left(\frac{f_i}{f_u} \right)^d \frac{t^b}{a^b}$$

in which

Δf_r = relaxation stress loss at time t

f_i = initial stress

f_u = ultimate strength of steel

t = time from application of initial stress in hours

g, d, b = constants determined by regression analysis.

For the strand the values of g, b, and d were 0.0488, 0.274 and 5.04 respectively. The authors recommended that their equation be used up to 9,000 hours, representing the upper limit of their test data. No information on ultimate loss was presented.

In 1963 a study was made by Cahill and Branch⁴ on relaxation of a new wire product, the "stabilized wires". A new method of extrapolation was used based on a linear relationship between logarithms of the load loss rate (in lbs. per hr.) and the time (in hrs.)

$$\frac{d}{dt} (\Delta f_s) = at^b$$

$$\Delta f_s = At^B + C$$

Using this formula, Cahill showed that over a period of 30 years the new material is less susceptible to relaxation loss than the stress-relieved material.

An extensive investigation on this subject was carried out at the University of Illinois during the early 1960's. Magura,

Sozen, and Siess¹⁹ reported their results in 1964, together with an extensive review of work done by previous researchers. The object of their investigation was to study the effects of time, level of initial stress, type of wire, and prestretching on the relaxation loss of prestressing wire. The authors arrived at an equation which relates the remaining stress to time and initial stress. The express is:

$$\frac{f_s}{f_i} = 1 - \frac{\log t}{10} \left(\frac{f_i}{f_y} - 0.55 \right)$$

$$\text{for } \frac{f_i}{f_y} \geq 0.55$$

where

f_s = the remaining stress at any time after prestressing

f_i = initial stress at release

t = time, in hours

f_y = yield strength

In the usage of the above formulation, the loss occurring before release should be subtracted from the total loss predicted, with f_i taken as the effective stress at release. The authors stated that it is not strictly justifiable to project the conclusions from their test to longer durations and different conditions.

To account for the strain variation due to elastic

shortening, creep, and shrinkage of concrete, H. K. Preston modified the foregoing formula to evaluate the loss of stress over finite intervals of time.

$$\Delta f_r = \frac{\log t_2 - \log t_1}{10} \left(\frac{f_i}{f_y} - 0.55 \right) f_i$$

where

Δf_r = Relaxation loss in time interval t_1 to t_2

f_i = Steel stress at time t_1

t_1, t_2 = Time at the beginning and end of the time interval, respectively.

The accuracy of estimation obviously depends upon the number of time intervals used in the calculation. Preston recommended a minimum of three intervals: before transfer, from transfer to the application of full permanent load, and thence to the end of the service life of the member.

In a paper presented before the Australian Institution of Engineers in 1965, J. M. Antill³ reviewed earlier researches on relaxation and included a number of conclusions and suggestions. Contrary to earlier conceptions, the relaxation loss at 1,000 hours represents less than half of the ultimate loss. The rate of relaxation increases rapidly with temperatures above 20° C. For initial stresses below 0.50 ultimate strength, the relaxation loss may be considered negligible for practical purposes. He also asserted that a high degree of accuracy in the estimation of loss values is not warranted, since the quantity of practical

significance is the residual stress remaining in the tendon.

A five-year investigation was carried out at the University of New South Wales in Australia. A. J. Carmichael⁵ reported in 1965 the results of this study. The test results showed that the stress relaxation continued far beyond 1,000 hours. The ratio of stress loss at 10,000 hours to that at 1,000 hours was 1.34 for 0.161-in. diameter wires, and 1.40 for 0.200-in. diameter wires. Further work has indicated the average stress loss at 50,000 hours to be 1.6 times the stress loss at 1,000 hours. An equation based on basic creep laws was developed and suggested as a promising prediction equation. Also, the equation suggested by Magura, Sozen, and Siess seemed to be satisfactory up to 1,000 hours.

Engberg⁸ of Sweden reported in 1966 that his test results showed the stress relaxation to be a linear function of the logarithm of the testing time. The total relaxation after four years was 9.5 percent for the preloaded wire, and 10.25 percent for the wire tested as delivered. By linear extrapolation, it was found that the two curves corresponding to these test specimens, intersect after some sixty years at a stress relaxation of about 13.5 percent.

2.2 Review of Design Recommendations

As described in the previous section, most investigations on relaxation dealt with single wire specimens. Testing of twisted wires or prestressing strands are very few indeed. Moreover, almost all previous experiments were conducted on either a constant length, or a constant load, basis. Modifications of the research results

are therefore necessary before application can be made in design.

The inadequacy of the provision in the several U. S. design codes have been pointed out in Chapter 1. The ASCE-ACI joint Committee listed the several primary sources of prestress loss, but did not provide any guide in the evaluation of the several coefficients. The AASHO and PennDOT standard designs are based on lumped sum loss values. In the Bureau of Public Roads Criteria³⁰, the relaxation loss is specified at the fixed 4% of the initial stress.

In an effort to provide a better guideline for the designers of prestressed concrete members, the Prestressed Concrete Institute established a Committee on Prestress Losses in 1968 to study this problem and to make recommendations. In their recommendation³², the Committee adopted H. K. Preston's method for strands but increased the minimum number of time intervals to four and the minimum initial stress level to $0.60 f_y$. For other types of prestressing element, the Committee recommended following the manufacturer's suggestions with the support of adequate test data.

Recommendations on steel relaxation given in various foreign codes⁷ may be categorized into three major groups:

1. Qualitative discussion (Germany, Austria, Finland, Poland).
2. Flat rate, or flat value (Denmark, Italy, Belgium, England).
3. Detailed procedure, or suggested equations (Russia, Holland, European Concrete Committee).

The German and Austrian Codes (1953 and 1960 respectively) refer to creep in steel, and indicate that it will become noticeable only if the stress is above the creep limit. They also note that creep ceases within a few days if the stress is sufficiently below the ultimate tensile strength. Over-stressing is recognized as having a beneficial effect.

The Finnish Code (1958) deals very briefly with relaxation of steel, and requires relaxation tests to be performed for a duration of at least 120 hours.

According to the Polish Provisions, the relaxation losses may be neglected for steel wires of diameters 1.5 and 2.5 mm, if maximum stresses are maintained within the permissible limits. Similarly, it is permissible to neglect relaxation losses in wires of diameters 5 and 7 mm in post-tensioned elements if, before anchoring, the steel is over-stressed. Over-stressing is to be achieved by increasing the given maximum stress in steel by 10% and maintaining it at this level for at least ten minutes before anchoring.

The Danish Code, as early as 1951, contains quantitative provisions on the creep strain of steel. The following values are specified:

for $f_i = 0.80 f_u$	$\epsilon_{PL} \approx 0.1 - 0.2\%$
for $f_i = 0.75 f_u$	$\epsilon_{PL} \approx 0.05\%$
for $f_i = 0.45 f_u$	$\epsilon_{PL} \approx 0$

The following guidelines are contained in the Italian Code (1960):

1. "In the case of beams post-tensioned with cables, relaxation losses can be taken as 7% of the initial tensioning stress."

2. "In pre-tensioned beams these losses can be taken as 12% of the initial stress if the tendons are individual wires, and as 14% if the tendons are strands."

3. "The loss of stress over an infinite time can always be estimated as twice the average on at least two specimens subjected to 120-hour relaxation tests at the initial tensioning stress in the case of post-tensioned beams, and at 2.5 times that average loss in the case of pre-tensioned beams."

The Belgian Code (1960) contains an overall estimate of the total loss including elastic shortening, shrinkage, creep, and relaxation of steel. For pre-tensioned tendons directly embedded in concrete the recommended value is 20% of the initial prestress, provided that the stress in the tendons at time of transfer exceeds 60 kg/mm^2 (84 ksi).

The British Standards Institution (1965) tentatively recommends a flat value for the loss of stress due to creep of steel. A value of 15,000 psi is suggested for stress-relieved wires, or where the wire has been subjected to a 10% over-

stress for a period of two minutes during tensioning. Any further reduction should be based on tests of at least 1,000 hours duration with an initial stress of the tensile strength of the wire.

The Russian Code recommends the following formula for computation of the ultimate loss due to relaxation of steel.¹⁴

In high-strength cold-drawn wire

$$\Delta f_r = (0.27 \frac{f_i}{f_u} - 0.1) f_i$$

In hot-rolled reinforcement

$$\Delta f_r = 0.4 (0.27 \frac{f_i}{f_u} - 0.1) f_i$$

If $f_i \leq 0.37 f_u$, $\Delta f_r = 0$

where

Δf_r = loss in stress units

f_i = initial stress value

f_u = ultimate strength of steel

It is interesting to note that the Russian Code anticipates relaxation losses for initial stresses as low as $0.37 f_u$. Many studies set this value not less than $0.50 f_u$.

The Dutch Code (1961) explains the dependence of the relaxation upon the ratio of the initial stress to the guaranteed tensile strength of the steel and upon shrinkage and creep strains in the concrete. A table is provided which gives the loss as percentage of initial stress. For usage of the table, the values of

the initial stress, shrinkage and creep strain are required. Linear interpolation between the values of the table is permissible.

The European Concrete Committee (Comité Européen du Béton, abbreviated CEB) suggests the following procedures for estimating relaxation loss in their provisional practical recommendations for prestressed concrete (June 1966).

"The relaxation diagram of steel, tested at constant length and temperature, as a function of time and of the value of the initial stress applied to the steel, should be determined experimentally by means of the testing method recommended by RILEM (International Association of Testing and Research Laboratories for Materials and Structures).

"These diagrams should be plotted for initial stresses respectively equal to 65% and 80% of the characteristic failure strength of the steel. (CEB defines the characteristic failure strength as the 0.1% offset proof stress which is equated or exceeded by 95% of the test results assuming a normal statistical distribution.)

"The particular values to be considered are the value of the relaxation at the end of 1,000 hours (and) the tangent at this point of the diagram corresponding to 1,000 hours, allowing extrapolation up to a period of 100,000 hours (approximately eleven years)."

The CEB recommendations observed that the relaxation loss at 1,000 hours is between 2% and 8% for an initial stress of

65% characteristic strength, and between 8% and 12% for 80% initial stress. Furthermore, it is noted that the value of the total relaxation can be deduced from the 1,000 hours relaxation by applying an amplification factor between 1.5 and 2, depending on the shrinkage and creep - strains of concrete. For initial steel stress between 65% and 80% of the characteristic strength, CEB recommends linear interpolation.

In summary, at the present time, research work is being done on the relaxation of steel, but has not yielded sufficient long-term information. Qualitatively, the phenomenon was described and its nature clarified. The factors that affect relaxation loss were identified and the long-term nature of relaxation experimentally proved. Quantitatively, several investigators attempted to formulate expressions for prediction of the stress loss. The proposed expressions generally fit the test data used, but their validity for prediction, particularly for long-term projection, remained unproven.

3. RELAXATION STUDY

3.1 Purpose and Scope

Relaxation of prestressing strands is significant because of the high level of stresses. Many of the earlier researchers of relaxation stress loss claimed that the stress would reach a stable state in a few hours and that the relaxation loss represented only a very small fraction of the initial stress. More recently, however, test results of longer duration have become available, and it has been established that relaxation does extend over a long period of time, and that it could amount to as high as 20% of the initial stress.

It is the ultimate purpose of this project to provide an expression for the prediction of relaxation loss, accurately over a short period (one to two years), and reasonably well for the total loss over the entire life of the structural member (say at the end of fifty years).

It is also speculated that the relaxation loss for the life of the member may be predictable from short-time test data (100 hours - 14 days). This possibility will also be investigated.

3.2 Test Variables

3.2.1 Manufacturer

The three main suppliers of prestressing strands in Pennsylvania are: Bethlehem Steel Corporation, CF & I Steel

Corporation and United States Steel Corporation. The prestressing strands from all three manufacturers are subjected to ASTM standards. However, due to differences in the chemical composition, the kind and extent of treatment, and other factors, a difference in their relaxation behavior could be expected. Therefore, prestressing strands from all three manufacturers were included in this study.

3.2.2 Type and Size of Strands

Since the study is mainly concerned with prestressed bridge members, wherein 7-wire stress-relieved strands of the special grade (270 k) are used almost exclusively, only this type of strand was tested. Two strand sizes, 7/16 in. and 1/2 in. nominal diameter, were included.

3.2.3 Initial Stress Level

In all of the previous investigations dealing with the relaxation problem, the importance of the initial stress level and its direct effect on prestress loss were recognized. In this investigation, three primary stress levels were selected, representing an upper limit, a lower limit, and an intermediate value of the initial stress. The three values are, respectively: 80, 50, and 65 percent of the guaranteed ultimate tensile strength (GUTS). The 80 percent value, which is slightly below the conventional yield strength of the strand, can be looked upon as the practical upper limit of the initial stress. The 50 percent, on

the other hand, is selected as a lower limit, below which the relaxation loss can be neglected. The intermediate stress level of 65 percent is chosen at approximately the same value as prevailing in an actual pre-tensioned bridge member immediately upon transfer. It is noted here, that the European Concrete Committee (CEB) recommended the establishment of relaxation curves at similar initial stress levels, 65% and 80% of the characteristic failure strength respectively. An additional stress level of 70% was used in two of the test specimens. The purpose is to detect any abrupt change in the relationship between the behavior of the strands and the initial stress level near the conventional yield strength level. Two 7/16-in. strands from manufacturer B fractured before reaching the intended 80% initial stress level. Their replacement specimens were tested at a slightly lower initial stress level of 75% GUTS. (Further discussion in Appendix 3.)

3.2.4 Type of Loading

Theoretically, creep is defined as the increase of strain under constant load or constant stress. Relaxation is the decrease of stress under constant strain. Both phenomena share the property of being time-dependent and are principal factors in any long-term study involving stresses and strains. The data obtained from a constant load test are strain quantities (creep strain), while the results of relaxation tests are given in the form of stress quantities (prestress loss).

The actual experience of a prestressing strand

contained in a concrete member is different from both of the above. Because of the creep and shrinkage of concrete and fluctuations in superimposed loads, the length of the concrete member, and consequently the length of the strand, changes. This change of strain causes a deviation from a pure relaxation type of situation. At the same time, the tendon is relieved from some of its stress, and the basic condition for creep is violated. In the actual situation, a decreasing strain is combined with a decreasing stress. Nevertheless, the conditions are more comparable to that of a relaxation test than that of a creep test. For this reason the major part of the tests in this investigation were constant length (relaxation) tests. Description of relaxation specimens will be given in Chapter 5.

3.2.5 Other Variables

There are a number of other variables that might affect the relaxation loss. Several investigators have reported that the relaxation loss increases substantially with an increase in the ambient temperature^{19,20}. However, these investigators generally referred to temperatures far beyond 100° F. As the pre-tensioned bridge members are not expected to be exposed to such extreme temperatures except for a short initial curing period, the significance of temperature variation in the present study is judged to be small.

It has also been reported that maintaining a high stress for a short period of time before anchoring to the desired initial stress (prestressing or prestretching) results in

an appreciable reduction of the relaxation losses.

These effects of temperature variations, prestressing, and other factors were not included in this study.

3.3 Preliminary Investigation

Preliminary results on 34 constant length (fixed strain) specimens indicated the following conclusions²⁴:

"1) The relaxation loss depends strongly on the initial stress in the strand.

2) In general, 1/2 in. strands suffer a higher relaxation loss than the 7/16 in. strands.

3) The loss characteristics from the three manufacturers do not differ significantly during the initial period."

Details of these preliminary observations are contained in a report by E. G. Schultchen, at the Lehigh Prestressed Concrete Committee meeting, July 1969, and in Progress Report No. 3 of the project (Fritz Engineering Laboratory Report No. 339.4, by Schultchen and Huang).

3.4 Additional Tests

The relaxation stress-time curves can be visualized as countour lines on a surface in the stress-strain-time three-dimensional space, as shown in Fig. 1. A surface can be established from the relaxation test data, and information regarding constant load or other specified strain variations can then be derived from this surface. To verify the results of such

operations, additional tests as described below are included in this study, but their results are not included in this report.

3.4.1 Simulation Study

As was pointed out earlier, the actual situation of a prestressing strand under load is neither purely relaxation, nor purely creep. To study the effect of varying deformation, twelve simulation specimens were fabricated and are being tested at Fritz Engineering Laboratory. Each simulation specimen is a pre-tensioned concrete member with a concentric unbonded prestressing strand. It is believed that the concrete would provide a strain variation similar to that of the actual member. Tensile force remaining in the strand is measured in a manner similar to the relaxation specimens according to a preset schedule. Simultaneously, concrete strain readings are obtained by means of a Whitmore gage, from a number of gage points on the four faces of the specimens. The data obtained has not yet been analyzed and no conclusions can be made at this stage.

3.4.2 Constant Load Test

"Creep and stress relaxation are kissing cousins but they are not interchangeable", (T. C. Hansen¹⁰). In the quoted paper, Hansen suggested an approximate method for estimating one from the other that gives good results for stresses well below creep rupture. In his equation, creep strain and stress after relaxation are related, with the values of the initial stress and

initial strain as parameters.

Reference is again made to the three-dimension surface relating stress, strain, and time, from which information regarding creep can be derived. To verify the results of these computations six constant load (creep) tests will be performed.

4. TEST-SETUP

4.1 Relaxation Frame & Jacking and Measuring Assembly

The relaxation frame is made up mainly of two 6 in. x 4 in. x 1/2 in. steel angles, with long legs upright and 1 in. apart. This loading frame is 10 feet in length and is supported near its ends on a steel storage rack designed especially for this purpose. Five plates at 2 ft.-3 in. spacing are tack welded to the outstanding legs of the double-angle section. To maintain the back to back distance between the long legs, seven spacers are used at spacings of 1 ft.-6 in. The strand specimen is placed at the centroid of the double-angle section and anchored to 1 in. end plates by means of strand chucks. Fig. 2 shows some details of the loading frame, while Fig. 3 gives a general view of the complete setup.

The jacking and measuring assembly consists of a number of parts extending between the end plate at the jacking end of the frame and the pulling rod of the hydraulic jack. As Schematically shown in Fig. 4, the end plate and the strand chuck are separated by a load cell and a device for the control of the initial elongation in the specimen. The device is composed of a number of spacers, D, and a fine adjustment bolt, B, which screws into the bearing plate A. Fig. 5 shows the jacking end of the frame with the above-mentioned arrangement.

For the detection of possible strand slippage in the

Strandvises, dial gages were mounted on top of each end plate. The plungers of these dial gages rested against targets attached to steel straps clamped on the strand specimen. Readings on the dial gages were taken on both ends of the frame before and after each force measurement, for a period of fourteen days starting from the initial stretching.

4.2 Load Cells

4.2.1 Description

The load cells used for the force measurement were especially designed to yield a high degree of sensitivity. They are made of 2014-T6 aluminum alloy, in the shape of a hollow cylinder, with a length of 5 in., an inner diameter of 7/8 in. and an outer diameter of 1-3/4 in. Eight EA-13-125TM-120 type strain gages are mounted on the outside of each cylinder, four in the longitudinal direction, and the other four lateral. These strain gages are connected into two independent Wheatstone Bridges. Strain readings are taken from the bridges by a digital strain indicator (Bean Model 206B).

4.2.2 Calibration

The test data used in the analysis are readings obtained through the load cells. In order to guarantee maximum reliability, much attention was paid to the handling of the load cells, and a careful procedure was followed in their calibration.

Two series of load cells (Series A and O) were used in

the relaxation study. Load cells were calibrated five or six in series on a Tinius Olsen 120K-hydraulic testing machine at Fritz Engineering Laboratory. Two loading and one unloading runs were performed. The calibrated range of loading was from 1 kip to 34 kips. Readings were taken at each multiple of 5 kip, as well as at the limits of the loading range.

A computer program (PROGRAM CALIB) was written to perform regression analysis for the calibration data. It should be pointed out that the actual loading, as opposed to the nominal loading, was recorded and used in the regression analysis. The final calibration coefficients were determined by the following procedure:

- 1) A regression analysis is performed based on all raw data.

- 2) Based on results of step (1) data points with large deviation are rejected, and a new regression analysis is performed based on all data remaining. (Criterion for rejection was chosen to be two times the standard error of estimate, SEE.)

- 3) The above procedure, steps 1 and 2, was used twice for each bridge channel:

- (a) Expressing Indicator readings in terms of
Load readings $I = A.L$

- (b) Expressing Load readings in terms of
Indicator readings $L = B.I$

The average of B and the reciprocal of A is used for later force determination.

The calibration data for Series A showed some abnormality, as shown in Fig. 6. The following modification was used in their regression analysis:

- 1) Data obtained from the unloading run was excluded from the regression analysis because of obvious bias (hysteresis type of off-set).

- 2) Data from lowest load step (1 kip) were also excluded because of the large error included in the load readings of the lower range of the testing machine.

Fig. 6 is a qualitative picture of the path followed at each run and the data excluded.

It should be pointed out, that even after modification, a few load cells of Series A (data sets 8 and 9) still showed a certain amount of bilinearity. However, since no preference between runs 1 and 3 could be made, both runs were used in the analysis.

As a result of the regression analysis the following conclusions were drawn:

- 1) In the majority of cases, the load correction improved the prediction relationship. In series O which included 25 load cells, or 50 channels, the standard error of estimate was reduced for 26 channels. In series A, 48 out of 62 channels

showed improvement upon inclusion of load correction.

2) The difference between calibration coefficients B and $\frac{1}{A}$ is not significant, except for those data with bipolarity (Series A, data sets 8 and 9).

The results obtained from the above-mentioned analysis show that each unit of the indicator reading corresponds to a force of approximately 8 pounds, which is less than 0.06 percent of the initial tension in the specimen. The range of this calibration constant was from a lowest value of 7.89 pounds per unit reading to a highest of 8.13.

5. TEST SPECIMENS

5.1 Tension Strands

In the United States, prestressing tendons for pre-tensioned bridge beams are almost exclusively uncoated seven-wire stress-relieved strands. The standard strands (ASTM A-416) are made of high-carbon steel. The raw material, in the form of rods, is heat-treated and then cold-drawn into wires of small diameter. Strands are made of six wires twisted around one central straight wire of a slightly larger diameter.

Stress-relieving is a controlled time-temperature heat-treatment process. By heating the strand to a controlled temperature, residual stresses induced during manufacturing and stranding are relieved without destroying the fibrous structure of the material. This process also increases the elastic limit and the ductility of the strand.

A-416 standard strands are required to have an ultimate tensile strength of 250 ksi. In 1962, a special grade of strands, with an ultimate tensile strength of 270 ksi was introduced, and quickly dominated the pre-tensioned prestressed concrete industry. Coupled with a slightly larger size, the strands of 270 k grade have a load capacity approximately 15% higher than the standard strands of the same nominal diameter.

The specimens included in this study were stress-relieved 7-wire strands of the special grade. Tensile tests were

performed on the strands after their shipment to Lehigh University. Results of these tests and other information relevant to the tested strands are compiled in Appendix 1.

5.2 Distribution and Designation

A total of 40 relaxation specimens were tested, representing three manufacturers, two strand sizes, and five initial stress levels. Table 1 shows the distribution of specimens for each combination.

Each specimen is designated by a two-letter, two number, individual code. The first letter refers to the strand size. The second identifies the manufacturer. The first numeral designates the initial stress level, while the second identifies the several repetitive specimens in sequential order. Fig. 7 provides a key to this designation with all possible combinations.

5.3 Force Measurement

5.3.1 General

The main requirement in force measuring for relaxation tests is that the measurement must be accomplished while the strain is maintained constant. Various methods had been used in the past. They generally fall into one of four major categories: the vibration method, the lever method, the balance method, and the deflection method. A short description of each can be found on page 14 of Reference 19.

The method used in this study involves direct

measurement of the force by means of a carefully calibrated load cell, connected in series with the test specimen. This technique is similar to that employed by the balance method.

The axial deformation of the load cell is small compared to the length of the tested strand and can be neglected. This will be further discussed in Section 6.5.

5.3.2 Measurement of Initial Tension

At the initial stretching of a relaxation specimen, an additional load cell (G) is used outside of the jacking ram in conjunction with the internal load cell (E), as shown in Fig. 4. At the beginning, a zero reading on the internal load cell is taken, and the desired final reading after anchoring is calculated according to the desired initial stress.

The strand is stretched until the external load cell shows a load slightly higher than the required value. Several spacers are placed between the adjustment screw (B) and the load cell (E), as shown in Fig. 4. The adjustment screw is then turned out of the end plate until a snug fit is reached. A few repetitions are sometimes needed until the desired internal load cell reading after anchoring is accomplished. Tables 2 and 3 give the actual initial stress percentages obtained for each specimen. As can be seen, the values are quite accurate. The maximum deviation from the desired value was only 0.7%. In the majority of cases, this deviation was less than 0.1%.

5.3.3 Subsequent Measurements

For subsequent measurements, only the internal load cell is used. The procedure of measurement includes the following three steps:

- 1) Taking readings on the loaded internal load cell.
- 2) Pulling on the strand coupler until pressure between the spacers disappeared. This can be detected by hand-touch of these spacers. The load cell is now under zero load. The current zero readings are taken.
- 3) Without changing the settings of the spacers or the adjustment screw, the jack is released. A second set of readings is taken on the reloaded internal load cell.

The reason for excluding the external load cell in subsequent force measurements, is that the internal load cell yields much more reliable and consistent results. This is discussed further in Section 6.5.

5.4 Test Duration and Age

Readings after initial stretching are taken according to a preset schedule. In Table 4 are given the selected intervals up to 2,000 days. In the early stage, readings are taken in very short intervals, which become longer as the specimen ages.

It was pointed out earlier that relaxation of steel is a long-term phenomenon, which may not be completed within the

duration of a test program, which usually does not extend over more than five years. Consequently, the significance of any study depends on the length of its test program. As of February 1, 1970, the age of the oldest specimens in this investigation is 444 days (approximately 10,000 hours), twelve specimens have reached this age. Forty percent of all specimens have been under tension more than 300 days; sixty-five percent more than 200 days, and ninety-five percent more than 100 days.

In spite of the relatively short age of these specimens, it is felt that a reasonable estimate of the prestress loss could be made based on the information collected.

6. DATA REDUCTION AND ANALYSIS

6.1 Preliminary Reduction

The experimental data collected in this investigation are indicator readings from the calibrated load cells. Each load cell yields two sets of data at each force measurement, one from each channel. Each set of data consists of three readings, two loaded readings before stretching and after release of the specimen, and one zero reading when the force in the specimen is completely resisted by the jacking assemblage. Thus, two differential readings are obtained for each channel. The average value of the two is taken, and is used in further analysis. Consequently, for each force measurement two pieces of data (averaged differential readings) are obtained, and each is directly proportional to the force remaining in the strand, by means of the respective calibration constant. These hand-reduced differential readings are used as input data for a computer program (LISTREX), which performs the preliminary reduction. This program reduces the input data into the percentage loss of force in specimen. Basically the following operation is performed in this early reduction:

$$\text{Percentage Loss} = \frac{\text{Initial Force} - \text{Remaining Force}}{\text{Initial Force}}$$

At this stage, the loss values are carefully examined for unusual

variations, and the input data, which are reproduced in the computer output, are inspected for possible errors in hand calculations, card punching, and otherwise.

6.2 Method of Analysis

The problem of developing expressions for relaxation loss of steel, based on experimental data is, by nature, a statistical type of problem. It involves an attempt to find the geometric best fit of the available data. There is an additional complication. The selected expression must be suitable for the purpose of prediction over a long period of time, for which test data are not available.

The first step of the analysis was to treat the problem in the two-dimensional state, considering the relationship between prestress loss and time only. At the beginning, a rather complex expression²⁴

$$L = a_0 + a_1 t + a_2 \sqrt{t} + a_3 t^2 + a_4 \log t$$

was used with the intention of describing all features of the existing data. Simpler expressions were then examined, and their behavior studied for long-term or short-term applications. This led to the selection of a few good time functions, which were used in further analysis.

Up to this stage, the initial stress level was not included as a variable in the regression analysis. With the time

functions selected, the next logical step was to handle the problem in the three-dimensional space, and determine the surface that best describes the experimental data, using both time and initial stress as independent variables.

Based on this three-dimensional analysis, a functional expression for prediction of prestress loss is developed.

6.3 Two-Dimensional Analysis

6.3.1 Computer Program SRELAA

This program was authored by E. G. Schultchen, research assistant at Lehigh University. SRELAA performs regression analysis of relaxation test data with respect to time. The analysis is done for one single series of repetitive specimens (e.g. AB5). Linear combinations of the following subfunctions are permitted.

$$1, t, t^2, t^3, t^4, \log t, (\log t)^2, \sqrt{t}, e^{-t}, \frac{1}{t}$$

In addition, the hyperbolic function $\frac{At}{t+B}$, and the exponential function At^B can also be used. SRELAA can test, upon each submission, ten types of linear functions (maximum of 6 terms in each), the hyperbolic, and/or the exponential function. The basic procedure followed is the method of least squares, which is employed to furnish the equations necessary to determine the regression coefficients of the linear functions. The exponential and hyperbolic functions, on the other hand, are treated

separately. An iterative procedure is used to determine the regression coefficient B, while coefficient A is determined by linear regression. In this manner the need for linearization is eliminated. Beside evaluation of the regression coefficients, the program also computes the sum of squares of residuals (SS), the Standard Error of Estimate (SEE), and the fitted data for testing ages as well as for standard arguments of time.

With some modification the program SRELAA could also test the regression function $A(1 - e^{-t/B})^C$. In this case, either C or B must be selected by trial while the other coefficient can be evaluated by the iterative minimization process used for the exponential and the hyperbolic functions.

6.3.2 Selection of Time Function

The flexibility provided by the two-dimensional regression program, SRELAA, made it possible to test a large number of time functions for their suitability. Functions with more than three terms were not considered, since such long and complex expressions would not be practical. A total of twenty-six linear time functions were tried. Twelve of these contained two terms, the others contained three terms. A comparison was made based on the Standard Error of Estimate for the several expressions, and those with high SEE values were discarded.

The range of SEE was 0.29 to 3.29 for all two-term expressions, and 0.15 to 1.38 for the three-term expressions (The

computed percentage loss values ranged up to 13%.) The expressions selected for further investigation were:

$$L = A_1 + A_2 \log t \quad (6.1)$$

$$L = A_1 + A_2 \log t + A_3 (\log t)^2 \quad (6.2)$$

$$L = A_1 + A_2 \log t + A_3 \sqrt{t} \quad (6.3)$$

$$L = A_1 + A_2 \log t + A_3 \frac{1}{t} \quad (6.4)$$

In the above, L is loss in percent of initial stress, t is time in days, and A's are regression coefficients. The average standard errors of estimate, weighted by the amount of data in each series were: 0.50, 0.31, 0.35, and 0.38 for the expressions 1, 2, 3, and 4 respectively. About 1250 pieces of data were included in the calculation of these values.

The two non-linear time functions

$$\text{Hyperbolic Function } L = \frac{At}{t + B} \quad (6.5)$$

$$\text{Exponential Function } L = At^B \quad (6.6)$$

were also included and given special attention. Their weighted standard errors of estimate were 0.56, 0.36 respectively.

The next step was to compare the behavior of these selected functions. The basis for comparison was the consistency of each expression for the various series of specimens. For this purpose curves were plotted and the correlation of actual

relaxation data with fitted values was studied. The applicability of each function for long-term relaxation loss prediction was also of much importance. With this in mind, the following observations were made.

1) The hyperbolic function was included for its asymptotic nature, but it proved to be unsatisfactory. With a noticeably high SEE, this expression fits the data poorly. This function tends to predict an early completion of relaxation (after approximately 100 days) at a low value.

2) Expression (6.3) fits the experimental data well for the first 500 days, but it yields very high and unreasonable long-term prediction values.

3) Expression (6.4) does not fit the data for the initial period, up to 5 days. The asymptotic effect of the $\frac{1}{t}$ term was negligible, and overshadowed by the other terms. Thus, no particular advantage was detected for this expression.

4) Expression (6.2), $L = A_1 + A_2 \log t + A_3 (\log t)^2$, has the lowest SEE, and shows consistency in the nature of predicted values.

5) Judging solely by the magnitude of SEE, Expression (6.1) is inferior to Expression (6.2). On the other hand, it contains one fewer term, which is a desirable feature. Practicality has to be weighed against accuracy. Fig. 9 (semi-log scale)

shows clearly that the two-term expression is a crude fit of the test data, overestimating the loss for the initial period while underestimating it at later ages. The test data shows a distinct curvature which cannot be reflected by this linear relationship.

6) The exponential expression, $L = At^B$, is particularly interesting. Possessing the characteristic of simplicity, it also proves to be a very good fit for the initial 500 days (Fig. 9). It appears to be quite adequate for evaluating the relaxation loss during this initial period. However, for long-term prediction, this expression consistently yields relatively high values.

7) It was suspected that the long-term prediction capability may be improved by omitting the data for the earlier period in the regression analysis. However, several trial calculations showed the result to be unfavorable. Any omission of initial data proved detrimental in both the "goodness" of the fit, and consistency of behavior.

These observations show clearly that the three-term expression, $L = A_1 + A_2 \log t + A_3 (\log t)^2$, is the most satisfactory among all functions tried. On the other hand, the exponential function, $L = At^B$, was found to be quite as adequate in the first 500 days. It was decided to carry both functions into the three-dimensional analysis. It was felt that the exponential function could be used for short-term estimation, while the

linear expression could be employed for long-term prediction. Tables 5 and 6 contain a summary of the regression coefficients for all series of specimens as evaluated from the two-dimensional regression. The coefficients of the polynomial expression, A_1 , A_2 , and A_3 , fall in ranges 0.95 - 5.27, 0.69 - 2.78, 0.190 - 0.764 respectively. In the exponential equation, the coefficient A varied from 1.12 to 5.40, while the exponent B varied from 0.151 to 0.316. Despite the wide variety of the test series, the range of constant B is relatively narrow. It is therefore considered justifiable that in the ensuing 3-dimensional analysis, t^B could be treated as a separable function.

Neither of the two expressions indicated an upper bound for the stress loss as the time approaches infinity. Theoretically, however, it is believed that such is the case. Hence, another function, $L = A(1 - e^{-t/B})^C$ was investigated. [This model was suggested by Kingham, Fisher, and Viest⁽¹²⁾, and discussed in Chapter 2.] The results showed that this expression fitted the data quite well, but approached its asymptotic upper bound value in a short period of time, 300 - 500 days. The test data, on the other hand, showed a clear trend of increasing loss at such time. Therefore, it is felt that this expression would underestimate the loss at later ages. In contrast, although the semi-logarithmic polynomial does not indicate an upper limit, the values calculated from this expression at a time of 50 years appeared "reasonable". These values might be higher than the

actual values, but are considered acceptable. Further investigation of the asymptotic function should be made when more data become available.

6.4 Three-Dimensional Analysis

6.4.1 Computer Program SRELAB

This program performs a multiple regression analysis of the relaxation test data from all series of specimens supplied by the same manufacturer, and of one strand size (e.g. all AB specimens). This program can easily be modified to analyze all series from all manufacturers. The independent variables in this analysis are time and initial stress level, while relaxation loss is the dependent variable. The linear time subfunctions were purposely selected to be identical to those of Program SRELAA. Separate subroutines were written for the hyperbolic and exponential functions. Combined with each selected time function, the program is capable of testing, in one submission, eight different linear combinations of up to four stress subfunctions, $1, s, s^2, s^3$. Here s is the ratio of initial stress in the specimen, f_i , to the guaranteed ultimate tensile strength, f_u . A phase of data rejection is provided in each of the two main regression subroutines. Data which reflect large deviation from the fitted values from the regression analysis are excluded, and a second analysis is performed on the remaining data. SRELAB has a number of additional features, and a description of the program

is provided in Appendix 2.

The method of least squares was used for the linear expressions. In this case, the form of the regression function is:

$$\bar{L}(t,s) = \sum_{i=1}^{NF} \sum_{j=1}^{NG} a_{ij} F_i(t) G_j(s)$$

where:

$\bar{L}(t,s)$ = Fitted values of relaxation loss, in percentage of initial stress.

t = time; number of days after initial stretching.

s = stress variable, expressed as ratio of initial stress, f_i , to guaranteed ultimate strength, f_u .

F_i, G_j = time, and stress subfunctions respectively.

NF, NG = number of time and stress subfunctions respectively.

Let $L(t,s)$ be actual data. The aim of this analysis is to minimize SS, the sum of square of the residuals.

Thus:

$$SS = \sum^N (L - \bar{L})^2$$

where N is total number of data. Differentiating with respect to each regression coefficient, and equating to zero

$$\frac{\partial SS}{\partial a_{ij}} = -2 \sum^N (L - \bar{L}) \frac{\partial \bar{L}}{\partial a_{ij}} = 0$$

$$\sum^N (L - \bar{L}) F_i(t) G_j(s) = 0$$

$$\sum^N \bar{L}(t,s) F_i(t) G_j(s) = \sum^N L(t,s) F_i(t) G_j(s)$$

$$\sum^N \left[\sum_{k=1}^{NF} \sum_{l=1}^{NG} a_{kl} F_k(t) G_l(s) \right] F_i(t) G_j(s) = \sum^N L(t,s) F_i(t) G_j(s)$$

This yields NF x NG linear equations in terms of the regression coefficients. These coefficients are then calculated by solving these equations simultaneously.

The analysis for the exponential functions was more involved. The basic assumption that the time function is separable was made. Thus, the regression function may be written:

$$\bar{L}(t,s) = t^B \sum_{j=1}^{NG} a_j G_j(s)$$

$$SS = \sum_{j=1}^N (L - \bar{L})^2$$

$$\frac{\partial SS}{\partial a_j} = -2 \sum_{j=1}^N t^B (L - \bar{L}) G_j(s) = 0$$

$$\sum_{j=1}^N (t^B)^2 G_j(s) \left[\sum_{k=1}^{NG} a_k G_k(s) \right] = \sum_{j=1}^N t^B L(t,s) G_j(s)$$

Or, in matrix form

$$\sum_{j=1}^N (t^B)^2 \begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ G_{NG} \end{bmatrix} [G_1 \ G_2 \ \dots \ G_{NG}] \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_{NG} \end{bmatrix} = \sum_{j=1}^N t^B L(t,s) \begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ G_{NG} \end{bmatrix}$$

The last formulation represents a set of NG linear simultaneous equations, the solution of which yields the linear coefficients

a_1 to a_{NG} . Coefficient B is determined through an iterative procedure controlled by the magnitude of the sum of squares. The final value of B is the one which corresponds to the minimum sum of squares.

The analysis for the hyperbolic time function would be similar to that for the exponential function described above. The time function would take the form of $\frac{t}{t+B}$, where B is to be determined by the iterative method.

6.4.2 Selection of Stress Function

In the three-dimensional regression analysis, the only time functions considered were those which demonstrated desirable characteristics in the two-dimensional analysis. These include the three-term linear combination of logarithmic subfunctions, and the exponential time function. Consequently, the resulting general expression of loss had either of the two forms

$$L = \sum_{i=1}^{NF} \sum_{j=1}^{NG} a_{ij} F_i(t) G_j(s) \quad \text{or} \quad L = t^B \sum_{j=1}^{NG} a_j G_j(s)$$

A total of 8 stress functions (two contained three terms, the other six two terms) were tried. By inspecting the magnitude of the SEE, it was possible to narrow the choice to three combinations. They are:

$$G_j = 1, s \quad G_j = 1, s^3 \quad G_j = 1, s, s^2$$

When combined with the linear combination of the logarithmic function, these stress functions resulted in SEE values of 0.52, 0.31, 0.27 respectively. When combined with the exponential function t^B , the magnitude of SEE were 0.51, 0.34, 0.31 respectively. Further inspection of these three stress functions, as to their consistency with actual data (Fig. 10), showed clearly that a simple linear relationship between loss and stress should not be applied over the whole range of initial stress from $0.50 f_u$ to $0.80 f_u$. Of the three functions, the three-term combination $G_j = 1, s, s^2$ gave the best results, and it was selected for complete development. The two-term combination $G_j = 1, s^3$ could be used. It was rejected since, in addition to a slightly larger SEE as compared to the three-term expression, the cubic term also adds complexity to the calculations.

The parabolic stress function is applicable to the total range of initial stress considered in this investigation, namely $0.50 f_u$ to $0.80 f_u$. The curvature of the function, however, was found to be small in the lower range from $0.50 f_u$ to $0.65 f_u$. Further investigation of this character showed that the linear stress combination, $G_j = 1, s$, will quite satisfactorily approximate the true behavior in this range of low stresses. For practical purposes, the applicability of this linear combination could be stretched up to $0.70 f_u$, which should be considered the upper limit, beyond which the behavior sharply deviates from linearity.

In summary, stress function $G_j = 1, s, s^2$ is chosen to cover the whole range of initial stress, $0.50 f_u$ to $0.80 f_u$. The linear combination $G_j = 1, s$ can be used only if the initial stress is restricted within a narrower range of $0.50 f_u$ to $0.70 f_u$.

6.5 Comparison of the 2-D and 3-D Analyses

After the selection of the stress functions, the behavior of the two basic time functions in the three-dimensional analysis was closely investigated. Reference is made to Figs. 11 and 12, which compare these three-dimensional relationships to their two-dimensional counterparts. Fig. 11 shows no substantial change in the behavior of the second degree semi-logarithmic polynomial. In both analyses, the functional expression fits the test data very well. One should keep in mind that in the three-dimensional analysis, time functions were treated as unseparable, and all regression coefficients were directly dependent on both time and stress.

The exponential function, on the other hand, underwent some change (Fig. 12), particularly at the high stress level. A certain deviation can be seen, and the function does not give the very good fit of the 2-D analysis. From a practical point of view, however, the results may still be considered acceptable. In the worst case, the deviation in the magnitude of loss was ± 1 percent of the initial stress, and on the average about

0.5 percent. This deviation can be attributed to the fact that t^B was treated as a separable function, making B independent of stress. It was noted earlier (Section 6.3.2) that the value of B in the 2-D analysis was reasonably uniform, ranging from 0.151 to 0.316. Nevertheless, a variation in the B value exists. It is therefore to be expected that a three-dimensional analysis containing a separable time function could not produce a very close approximation. However, it should be emphasized once more, that the value of practical significance is the remaining stress in the strand after a certain time. A relative error in the loss percentage of 100 percent may mean only a small relative error in the value of the stress remaining.

6.6 Proposed Relaxation Equations

With the above observations in mind, the second degree semi-logarithmic polynomial is suggested as the best fit for the initial 500 days, and as a reasonable long-term prediction function. For the latter purpose, two fixed time points, twenty and fifty years were selected for comparison. The nine-coefficient general expression of loss has the form (as given on the next page):

$$\begin{aligned}
L = & (A_{11} + A_{12}s + A_{13}s^2) \\
& + \log t (A_{21} + A_{22}s + A_{23}s^2) \\
& + (\log t)^2 (A_{31} + A_{32}s + A_{33}s^2)
\end{aligned} \tag{6.7}$$

where:

L = loss in % of initial stress

t = time in days, after initial stretching

s = the ratio of initial stress to guaranteed ultimate strength,

$$\text{i.e. } \frac{f_i}{f_u}$$

A summary of the regression coefficients for each series is given in Table 7. The results of the regression analysis, computed from Expression (6.7) are shown in Figs. 14 through 18.

For a fixed time t , the expression reduces to:

$$L = A_1 + A_2 \frac{f_i}{f_u} + A_3 \left(\frac{f_i}{f_u}\right)^2$$

Table 9 contains the values of A_1 , A_2 , A_3 for the various series, for $t = 18250$ (50 years).

Although Expression (6.7) yields very close estimated values, with nine coefficients it does not lend itself to practical use. In this respect the exponential function has the advantage of being simple, yet providing reasonable results. It is thought that the exponential formulation can, for practical purposes, be used during the first 500 days. The expression has the form

$$L = t^B \left[A_1 + A_2 \frac{f_i}{f_u} + A_3 \left(\frac{f_i}{f_u} \right)^2 \right]$$

The values of these regression coefficients for each series are summarized in Table 10.

The analysis, so far, used data from each manufacturer and each size separately. This was done to reveal the effects of manufacturer, as well as strand size on the relaxation loss. The findings will be discussed later. In spite of the apparent effect of manufacturer and strand size, another multiple regression analysis of the combined data from all 39 series was performed. Since the ages of test specimens are different, this analysis was based on data from the first 149 days only, which corresponds to the age of the "youngest" specimens. This was done to avoid any possible bias, and to assure equal weight for all data from all specimens. Unified coefficients of the general expression of loss were obtained, and are shown in Table 11.

The prediction equations for long-term relaxation loss are:

For 50-year loss:

$$L = -20.11 + 82.61 \frac{f_i}{f_u} - 41.56 \left(\frac{f_i}{f_u} \right)^2$$

For 20-year loss:

$$L = -13.96 + 58.85 \frac{f_i}{f_u} - 24.15 \left(\frac{f_i}{f_u} \right)^2$$

The exponential formulation for possible evaluation of the loss during the initial 500 days is:

$$L = t^{0.201} \left[4.46 - 15.09 \frac{f_i}{f_u} + 18.91 \left(\frac{f_i}{f_u} \right)^2 \right]$$

Calculated values from these expressions are plotted in Figs. 19, 20, and 21.

The significance and applicability of these unified formulations will be discussed in a later chapter.

In the foregoing discussion, emphasis has been placed on the three-term parabolic stress function. It was pointed out earlier, that for initial stress ranging from $0.50 f_u$ to $0.70 f_u$,

the two-term linear stress function is adequate. The general equation of loss reduces to the following:

$$\begin{aligned}
 L = & \quad (A_{11} + A_{12} s) \\
 & + \log t \quad (A_{21} + A_{22} s) \\
 & + (\log t)^2 \quad (A_{31} + A_{32} s)
 \end{aligned}$$

the prediction equation to:

$$L = A_1 + A_2 \frac{f_i}{f_u}$$

and the exponential formulation fo:

$$L = t^B (A_1 + A_2 \frac{f_i}{f_u})$$

The regression coefficients in these equations for different series, can be found in Tables 8, 9, and 10 respectively.

With all series combined, the prediction equation for 50 years loss, and the exponential equation for the initial period take the following forms: (for $\frac{f_i}{f_u} = 0.50$ to 0.70)

$$L = 34.68 \frac{f_i}{f_u} - 6.90$$

$$L = t^{0.235} (5.80 \frac{f_i}{f_u} - 1.45)$$

6.7 Sources of Error

The reliability of any findings from this investigation is directly related to the reliability of the data collected in the relaxation tests. The following is a brief discussion of possible sources of error and their significance.

Elastic rebound of the relaxation frame, as well as that of the various parts of the anchoring and measuring assemblage, constitutes one of the major sources of error. As the force in the specimen decreases, the length of these elements does not remain constant, but elongates elastically, forcing the specimen also to elongate. As a result, the specimen force measured is higher than that in an ideal relaxation test. The error in the indicated stress loss was calculated to be in the range of 1.8 to 3.3 percent. This is considered small enough to be neglected for practical purposes.

Slippage within the anchoring device is another important source of error. Dial gages were used to detect any such slippage for an initial period of fourteen days. The dial gage readings were found to change considerably after each jacking operation, but remain relatively stable during the time between successive operations. Load cell readings before and after each jacking indicated that strand force does not change significantly by the operation. The change in dial gage readings is therefore attributed to instability of the target, vibration of the strand, and other mechanical disturbances. No correction was attempted on the basis of these dial gage readings.

A third possible source of error is the load cell. Under sustaining load, the zero reading of the load cell tends to drift (up to 50 indicator units). In order to eliminate this error, the load cell was completely unloaded for a new zero reading during each force measurement. The calibration of the load cell was carried out with much care, as described in Section 4.2.2. At the end of this investigation, the load cells will be recalibrated. Should there be any significant change in the calibration constants, a correction would be possible at that time.

Because of the elastic behavior of the load cells, the specimen force must be increased slightly before the load cell can be unloaded. This is inconsistent with the ideal requirement of measuring force without disturbance. However, the force increment required is only approximately 1% of the force being measured.

Considering also the short duration of these small disturbances, their effect on the final results is considered negligible.

In a number of occasions, the indicator unit was damaged and had to be repaired. This could have affected the response of the indicator, and led to deviations in test data. Deviations of this nature, however, would be easily observable when sufficient data before and after the indicator repair are plotted. Correction could be made at that time.

The foregoing lists a number of possible sources of systematic errors in the test data collected in this investigation. Considerable effort has been devoted to control these errors. While it may not be possible to eliminate or compensate for these errors completely, their effect is believed to be small. Keeping in mind that the quantity of real engineering importance is the prestress remaining in the strand instead of the losses, the significance of these possible errors in the estimation of one segment of the prestress losses is seen to be extremely low. For example, a gross mistake in the estimate of relaxation loss by, say, 20% would represent an error in the total prestress loss of perhaps 5%. The resulting error in the net effective prestress would be less than 2%, which is still tolerable.

In order to remove any systematic bias in the collected test data, the regression analysis was carried out in two stages. The first analysis included all test data collected from the series of specimen(s) being studied. Any data which deviated from

the regression curve by more than twice the standard error of estimate is then removed from the group. The second and final regression analysis was then performed on the remaining data.

7. DISCUSSION OF RESULTS

In the previous chapter, it has been shown that the relaxation behavior of stress-relieved strands can be described rather accurately within the initial period up to 500 days. In this regard Expression (6.7) gives the best results, while the exponential expression is also acceptable. It was also shown that reasonable long-term prediction can be achieved by means of Expression (6.7).

Despite the large variety of the several controlled parameters, the correlation between the fitted loss values and the experimental data was quite satisfactory. This is shown in Figs. 14 through 18 for individual series, based on results obtained from Expression (6.7). Tables 6 and 7 show that the standard errors of estimate for most specimens are reasonably low. The estimated relative error in the value of the stress remaining is well below 2 percent.

The experimental results show beyond any doubt, that relaxation continues far beyond the 1000 hours duration reported in some earlier studies. Even at an age of 444 days (over 10,000 hours), the experimental data still show a tendency of continued relaxation, without approaching any stabilized value. The percentage loss, in some cases, has already exceeded 13%, and the tendency of "bending over" reported in the preliminary report²⁴ did not continue.

For long-term projection, Expression (6.7) was applied to two fixed ages, arbitrarily chosen at twenty and fifty years. The results show that one-half of the 50-year loss occurs at around 500, 200, and 50 days for initial stress of 0.50, 0.65, and $0.80 f_u$ respectively. It can also be observed that the loss at 20 years corresponds to approximately 85 percent of the 50-year value. The predicted values at 20,000 days (approximately 54 years) were in ranges 8 - 14, 13 - 20, 16 - 24 percent of the 0.50, 0.65, $0.80 f_u$ initial stresses respectively. Table 12 contains a summary of the prediction values for each series after 500 days, and after 20,000 days.

Omission of data from the initial period for the purpose of better long-term projection yielded erroneous results. The use of short-term data, however, proved to have some significance. For prediction over the first 500 days, extrapolation extending from test data of short duration will yield acceptable results. Nevertheless, it is not recommended to extrapolate using data from less than 240 hours. For long-term projection data of 1,000 hours seem to be adequate. In general, it appears sufficiently safe to extrapolate the test duration by one order of magnitude (one cycle on logarithmic scale), but care must be exercised for further projection.

The effect of the initial stress on the relaxation loss appears to be very significant. Test results show that

relaxation is not negligible even for initial stresses below $0.50 f_u$ (some previous studies set the limiting lower initial stress close to this value). For this stress level the data shows losses as high as 7% of the initial stress after the first 500 days, and for some series, the probable ultimate loss reaches 15%. These values lead to the belief that these strands might undergo significant relaxation losses even when the initial stress is lower than $0.50 f_u$. It is interesting to note that the Russian code specifies $0.37 f_u$ as the limit below which relaxation loss is negligible. For the range of initial stress $0.50 f_u$ to $0.80 f_u$, it was obvious that the loss increases with increasing initial stress. The behavior over the whole stress range was not linear, and a parabolic relationship was proposed. This relationship, however, is quite close to linearity in the range $0.50 f_u$ to $0.70 f_u$. Above this range, the loss increases rapidly with increasing initial stress and the behavior deviates sharply from linearity.

The test specimens supplied by the different manufacturers suffered different relaxation losses. In Figs. 22 and 23, curves by the 3-D analysis are compared for the three manufacturers at three initial stress levels. In general, strands from Manufacturer C suffered lower losses than the other two. In some cases, the difference was significant. For the 7/16 in. strands, Manufacturers C and U show comparable losses, while strands from the third manufacturer, B, underwent consistently

higher loss. For the 1/2 in. strands, specimens from Manufacturers B and U show comparable behavior; both suffer high losses than those of Manufacturer C.

Two different strand sizes were included in this study, with nominal diameter of 1/2 in. and 7/16 in. respectively. Those of 1/2 in. size show, in general, higher losses than those of the smaller size (Figs. 24, 25, 26). This is particularly true for the 80% initial stress, and for time beyond the initial 100 days. While this effect of the strand size is rather mild for strands from Manufacturers B and C, it is quite pronounced for strands from Manufacturer U.

An attempt was made to apply one single analysis to the combined data from all series, disregarding any effect of manufacturer and strand size. A total of 1077 pieces of data was included in the regression analysis. The standard error of estimate developed by Expression (6.7) was 0.79, and the correlation with the actual data was satisfactory (Figs. 19, 20, 21). The predicted loss values at 500 days and 20,000 days are within reasonable limits, when compared with values obtained for individual series (Table 12). The induced relative error in the estimated value of the remaining stress is only two to five percent of the remaining stress. Thus, the unified formulations, mentioned in Section 6.4.2, may be used within the limitations of these practical considerations. For more accurate results, the effect of manufacturer and strand size should be taken into consideration.

All the expressions developed were based on relaxation (constant length) data. In an actual prestressed concrete member, the time-dependent concrete strain would cause the length of the strand to change, and the relaxation loss of prestress would be lower. A modification of formulas developed might be required, when results from the simulation and constant load study become available.

8. CONCLUSIONS

Based on results from forty relaxation (constant length) tests of duration up to 444 days, the following conclusions were drawn:

1. Strands from Manufacturer C have the lowest potential for relaxation loss, while strands from Manufacturer B suffer the highest loss.

2. In general, the 1/2 in. strands undergo higher losses than the 7/16 in. strands.

3. The relaxation loss depends strongly on the initial stress in the strand. There is an indication that losses are not negligible even for initial stresses below $0.50 f_u$. For the stress range $0.50 f_u$ to $0.80 f_u$, a parabolic relationship exists between loss and initial stress. For a narrower stress range $0.50 f_u$ to $0.70 f_u$, a linear relationship may be used.

4. Test results up to 444 days show no indication of approaching a finite value.

5. The best surface-fit for the test data was a second degree semi-logarithmic time polynomial, combined with a parabolic stress function. The exponential, 3-Dimensional expression $L = t^B [A_1 + A_2 \frac{f_i}{f_u} + A_3 (\frac{f_i}{f_u})^2]$ may, alternately, be

used for estimating the loss during the initial 500 days. For stress range $0.50 f_u$ to $0.70 f_u$, the square term $(\frac{f_i}{f_u})^2$ could be dropped.

6. For practical purposes, Expression

$$L = t^{0.201} [4.46 - 15.09 \frac{f_i}{f_u} + 18.91 (\frac{f_i}{f_u})^2]$$

yields acceptable results during the initial 500 days. The value at 50 years, which may be taken as the ultimate loss, may be estimated by the Expression

$$L = -20.11 + 82.61 \frac{f_i}{f_u} - 41.56 (\frac{f_i}{f_u})^2$$

For initial stress in the range 0.50 to $0.70 f_u$, the foregoing two equations may be replaced by

$$L = t^{0.235} (5.80 \frac{f_i}{f_u} - 1.45) \quad \text{and} \quad L = 34.68 \frac{f_i}{f_u} - 6.90$$

7. The predicted ultimate loss values (values at 50 years) are in ranges 8 - 14, 13 - 20, 16 - 24 percent of the $0.50 f_u$, $0.65 f_u$, $0.80 f_u$ initial stresses, respectively. Half of the ultimate loss occurs during the first 500, 200, 50 days for the three initial stresses, respectively. Also, the predicted loss at 20 years is about 85% of the ultimate value.

8. Omission of data from initial period for the purpose of long-term projection should not be attempted.

9. Extending short-term test data for longer term estimation and prediction is possible, but should be carefully done. In general, extrapolation for one additional cycle on logarithmic scale can be done safely.

It should be emphasized that the foregoing conclusions were based on test data covering a period of only approximately fifteen months, and consequently must be regarded as preliminary. As the investigation progresses, additional data will become available, to be compared with the prediction formulas developed herein. These formulas will be continuously re-evaluated and, when deemed desirable, revised.

Caution must be exercised in any attempt to apply the findings in the report directly to design practice. As pointed out in Chapter 7, extrapolation of relaxation data beyond one logarithmic cycle (ten-fold) in time may lead to erroneous results. Furthermore, on account of the rheological deformations of concrete, the "relaxation loss" of prestress in an actual member is expected to be significantly lower than that of the "relaxation specimens" covered in this report, which were subjected to constant elongation. The testing of constant load and simulation specimens, described in Chapter 3, were intended to produce information for the modification of the constant length relaxation formulas for practical use.

9. TABLES

Table 1 Distribution of Relaxation Specimens

<u>Nom. Diam.</u>	<u>Initial Stress (% f_u)</u>	<u>Manufacturer</u>		
		B	C	U
7/16 in.	50	2	2	2
	65	2	3	3
	75	2*	-	-
	80	-	2	2
<hr/>				
1/2 in.	50	2	2**	2
	65	2	2	2
	70	-	2	-
	80	2	2	2
<hr/>				

* Failed at 80% f_u

** Specimen BC51 was discarded

Table 2 Actual Initial Stress Values 7/16 in. Specimens

Initial Stress (In Percent of Ultimate Strength)

<u>Specimen</u>	<u>Average of Specimen</u>	<u>Average of Group</u>
AB51	50.06	50.01
AB52	49.97	
AC51	50.03	50.02
AC52	50.02	
AU51	50.05	50.04
AU52	50.02	
AB61	65.60	65.55
AB62	65.49	
AC61	65.12	64.99
AC62	64.74	
AC63	65.11	
AU61	65.47	65.07
AU62	64.89	
AU63	64.84	
AB71	76.50	76.43
AB72	76.36	
AC81	79.77	79.90
AC82	80.02	
AU81	80.13	80.05
AU82	79.97	

Table 3 Actual Initial Stress Values 1/2 in. Specimens

Initial Stress (In Percent of Ultimate Strength)

<u>Specimen</u>	<u>Average of Specimen</u>	<u>Average of Group</u>
BB51	49.45	49.75
BB52	50.05	
BC51	50.17	49.82
BC52	49.48	
BU51	50.29	49.99
BU52	49.69	
BB61	64.99	64.84
BB62	64.69	
BC61	65.08	64.89
BC62	64.71	
BU61	65.05	65.12
BU62	65.18	
BC71	70.08	70.05
BC72	70.02	
BB81	79.58	79.51
BB82	79.45	
BC81	80.19	80.20
BC82	80.21	
BU81	79.54	79.54
BU82	79.54	

Table 4 Typical Reading Schedule for Relaxation Specimens

<u>Number of Reading</u>	<u>Age of Specimen at Time of Reading</u>
1	0 (upon stretching)
2	4 hours
	<u>Days</u>
3	1
4	2
5	4
6	7
7	10
8	14
9	21
10	30
11	42
12	56
13	70
14	86
15	105
16	125
17	150
18	180
19	215
20	260
21	310
22	370
23	440
24	520
25	610
26	700
Subsequent Readings every 100 days	

Table 5 Coefficients of Equation $L = A_1 + A_2 \log t + A_3 (\log t)^2$

2 - Dimension Regression

<u>Series</u>	<u>A₁</u>	<u>A₂</u>	<u>A₃</u>	<u>SEE</u>	<u>No. of Data</u>
AB5	1.39	0.92	0.486	0.59	56
AB6	2.91	1.71	0.432	0.22	48
AB7	4.58	2.38	0.377	0.40	48
BB5	0.95	0.88	0.520	0.19	60
BB6	2.37	1.65	0.674	0.23	74
BB8	4.51	2.78	0.512	0.25	59
AC5	1.29	0.69	0.190	0.21	87
AC6	2.13	1.21	0.279	0.27	108
AC8	4.61	2.05	0.282	0.19	86
BC5	1.33	0.90	0.320	0.16	36
BC6	1.94	1.09	0.510	0.27	69
BC7	2.43	1.50	0.457	0.25	66
BC8	5.27	2.47	0.306	0.47	59
AU5	1.13	0.82	0.274	0.27	86
AU6	2.13	1.42	0.264	0.39	135
AU8	4.46	2.06	0.168	0.45	88
BU5	1.27	0.98	0.466	0.18	64
BU6	2.66	1.52	0.586	0.22	70
BU8	4.89	2.70	0.410	0.97	62

Table 6 Coefficients of Equation $L = At^B$

2 - Dimensional Regression

<u>Series</u>	<u>A</u>	<u>B</u>	<u>SEE</u>	<u>No. of Data</u>
AB5	1.47	0.271	0.59	56
AB6	3.07	0.215	0.22	46
AB7	4.63	0.192	0.42	47
BB5	1.12	0.316	0.21	61
BB6	2.63	0.248	0.27	75
BB8	4.77	0.202	0.40	61
AC5	1.34	0.202	0.20	87
AC6	2.24	0.199	0.29	110
AC8	4.84	0.151	0.20	85
BC5	1.43	0.243	0.15	35
BC6	2.09	0.233	0.29	70
BC7	2.62	0.220	0.25	65
BC8	5.40	0.162	0.50	58
AU5	1.25	0.242	0.28	88
AU6	2.32	0.200	0.46	139
AU8	4.56	0.151	0.54	90
BU5	1.46	0.268	0.21	67
BU6	2.79	0.228	0.18	68
BU8	5.12	0.183	1.0	62

Table 7 Coefficients of Equation

$$L = \sum_{i=1}^3 \sum_{j=1}^3 a_{ij} F_i G_j$$

$$F_i = 1, \log t, (\log t)^2$$

$$G_j = 1, s, s^2$$

<u>Series</u>	<u>i</u>	<u>A_{i1}</u>	<u>A_{i2}</u>	<u>A_{i3}</u>	<u>SEE</u>	<u>No. of Data</u>
AB	1	2.92	-13.07	19.94	0.43	149
	2	-0.42	0.77	3.78		
	3	-0.67	4.09	-3.57		
BB	1	1.84	-10.55	17.49	0.24	196
	2	1.02	-4.55	8.50		
	3	-2.01	8.50	-6.71		
AC	1	10.62	-37.22	37.18	0.23	281
	2	1.03	-3.92	6.49		
	3	-0.79	2.99	-2.08		
BC	1	19.93	-68.36	62.30	0.30	224
	2	6.45	-21.15	20.03		
	3	-2.31	8.63	-6.64		
AU	1	7.24	-26.89	29.27	0.39	308
	2	-1.13	3.57	0.54		
	3	-0.068	1.51	-1.54		
BU	1	3.99	-16.76	22.57	0.52	193
	2	3.64	-12.34	13.91		
	3	-1.87	7.71	-6.03		

Table 8 Coefficients of Equation $L = \sum_{i=1}^3 \sum_{j=1}^2 a_{ij} F_i G_j$

$$F_i = 1, \log t, (\log t)^2 \quad G_j = 1, s$$

<u>Series</u>	<u>i</u>	<u>A_{i1}</u>	<u>A_{i2}</u>	<u>SEE</u>	<u>No. of Data</u>
AB	1	-3.61	9.95	0.44	102
	2	-1.77	5.30		
	3	0.55	-0.09		
AC	1	-1.44	5.48	0.25	194
	2	-1.09	3.55		
	3	-0.13	0.64		
AU	1	-2.24	6.71	0.37	224
	2	-1.29	4.17		
	3	0.43	-0.26		
BB	1	-3.86	9.61	0.24	136
	2	-1.82	5.37		
	3	0.21	0.71		
BC	1	-1.34	5.32	0.26	166
	2	0.58	2.88		
	3	0.07	0.53		
BU	1	-3.36	9.23	0.20	136
	2	-0.92	3.74		
	3	0.10	0.76		

Table 9 Coefficients of Prediction Equation $t = 50$ years

$$\text{Equation } L = A_1 + A_2 \frac{f_i}{f_u} + A_3 \left(\frac{f_i}{f_u} \right)^2$$

<u>Series</u>	<u>A₁</u>	<u>A₂</u>	<u>A₃</u>
AB	-11.03	64.47	-28.77
BB	-30.30	124.39	-68.12
AC	0.67	0.37	27.07
BC	5.47	1.79	27.09
AU	1.20	15.56	3.61
BU	-14.45	70.64	-27.66

$$\text{Equation } L = A_1 + A_2 \frac{f_i}{f_u}$$

<u>Series</u>	<u>A₁</u>	<u>A₂</u>
AB	-1.16	30.90
BB	-7.81	45.39
AC	-8.44	32.23
BC	-2.52	27.21
AU	0.06	19.76
BU	-5.46	38.97

Table 10 Coefficients of Exponential Equation

$$\text{Equation } L = t^B \left[A_1 + A_2 \frac{f_i}{f_u} + A_3 \left(\frac{f_i}{f_u} \right)^2 \right]$$

<u>Series</u>	<u>B</u>	<u>A₁</u>	<u>A₂</u>	<u>A₃</u>	<u>SEE</u>	<u>No. of Data</u>
AB	0.211	1.63	-5.73	12.21	0.45	146
BB	0.231	-0.58	1.55	5.75	0.39	194
AC	0.169	4.91	-16.97	20.54	0.32	289
BC	0.198	11.11	-36.50	35.49	0.40	226
AU	0.178	2.93	-8.99	12.99	0.52	313
BU	0.225	1.59	-4.80	10.30	0.46	185

$$\text{Equation } L = t^B \left[A_1 + A_2 \frac{f_i}{f_u} \right]$$

<u>Series</u>	<u>B</u>	<u>A₁</u>	<u>A₂</u>	<u>SEE</u>	<u>No. of Data</u>
AB	0.229	-2.10	7.63	0.45	100
BB	0.263	-2.10	7.05	0.30	136
AC	0.200	-1.61	5.92	0.25	193
BC	0.227	-0.83	4.71	0.27	168
AU	0.211	-1.10	5.12	0.42	226
BU	0.238	-1.67	6.68	0.21	133

Table 11 Unified Coefficients of Relaxation Equation

$$L = \sum_{i=1}^3 \sum_{j=1}^3 a_{ij} F_i G_j$$

$$F_i = 1, \log t, (\log t)^2$$

$$G_j = 1, s, s^2$$

$$A_{11} = 9.92 \quad A_{12} = -35.77 \quad A_{13} = 36.88$$

$$SEE = 0.73$$

$$A_{21} = 2.20 \quad A_{22} = -7.33 \quad A_{23} = 9.50$$

$$\begin{aligned} \text{No. of} \\ \text{Data} &= 1077 \end{aligned}$$

$$A_{31} = -2.17 \quad A_{32} = 8.24 \quad A_{33} = -6.55$$

$$L = \sum_{i=1}^3 \sum_{j=1}^2 a_{ij} F_i G_j$$

$$F_i = 1, \log t, (\log t)^2$$

$$G_j = 1, s$$

$$A_{11} = -1.97 \quad A_{12} = 6.51$$

$$SEE = 0.63$$

$$A_{21} = -0.73 \quad A_{22} = 3.33$$

$$\begin{aligned} \text{No. of} \\ \text{Data} &= 748 \end{aligned}$$

$$A_{31} = -0.10 \quad A_{32} = 0.77$$

Table 12 Prediction Values of Relaxation Loss

<u>Series</u>	<u>Initial Stress Level</u>		
	<u>0.50 f_u</u>	<u>0.65 f_u</u>	<u>0.80 f_u</u>
<u>Values at 500 days</u> (% of initial stress)			
AB	7.37	10.90	14.63
AC	4.55	7.48	12.18
AU	5.45	7.88	11.18
BB	7.38	11.79	15.82
BC	6.16	8.50	13.90
BU	7.33	11.04	15.47
All Series			
Combined	6.01	9.24	13.14
 <u>Values at 20,000 days</u> (% of initial stress)			
AB	14.28	19.02	22.43
AC	7.80	12.59	18.58
AU	10.12	13.11	16.24
BB	15.08	20.08	25.94
BC	11.38	15.83	21.43
BU	14.25	20.14	24.70
All Series			
Combined	11.20	16.30	19.64

10. FIGURES

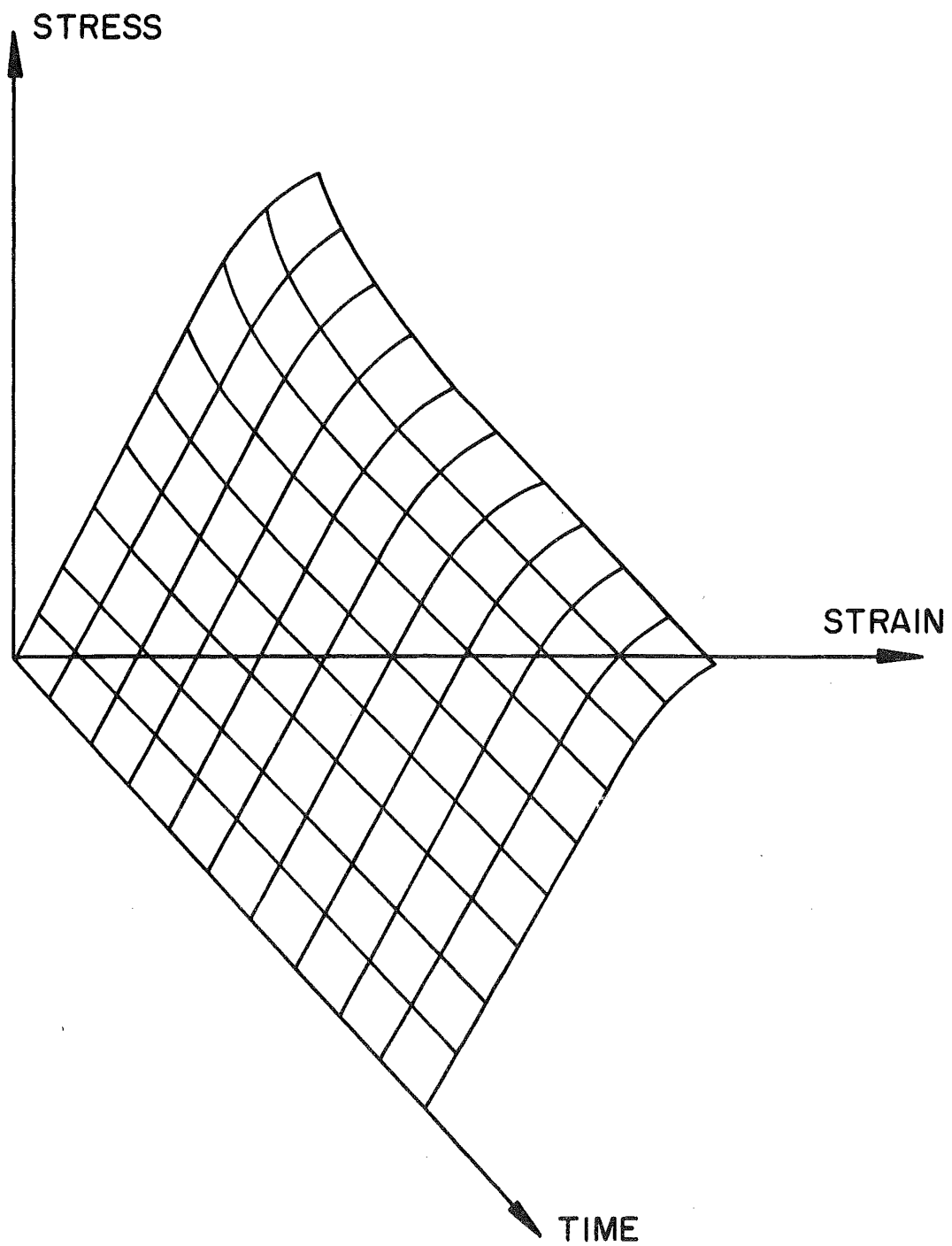


Fig. 1 Three-Dimensional Surface

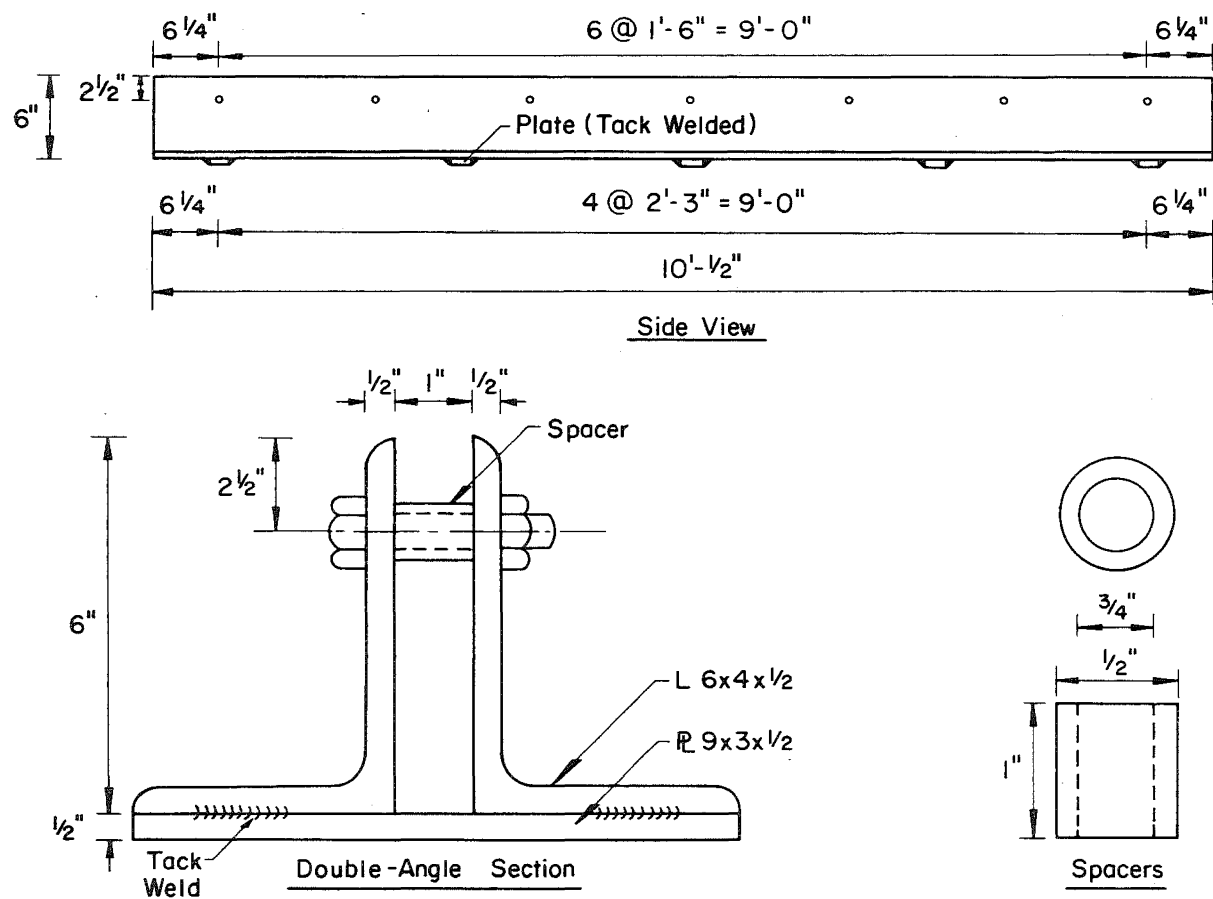


Fig. 2 Relaxation Frame

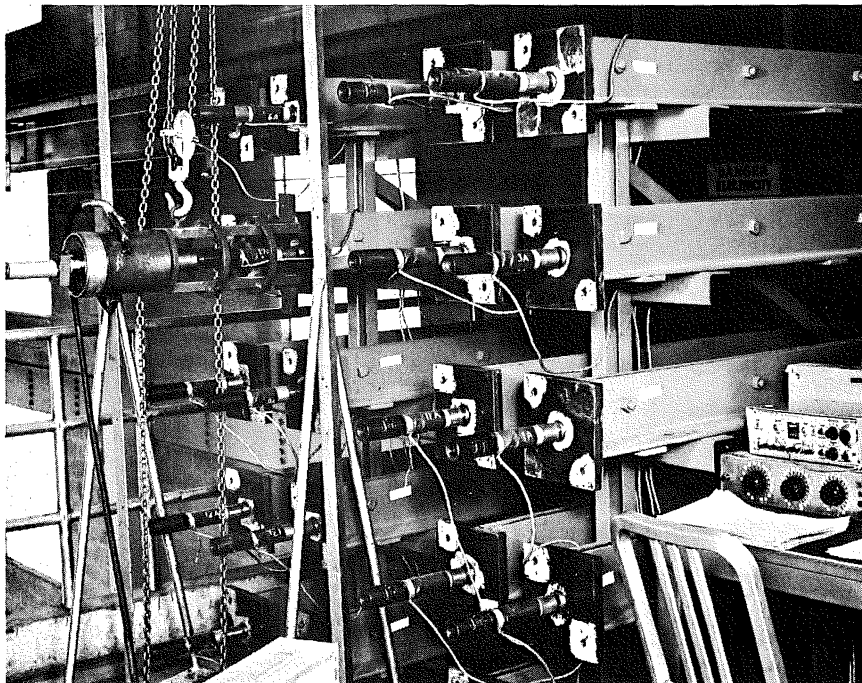


Fig. 3 General View of Relaxation Test - Setup

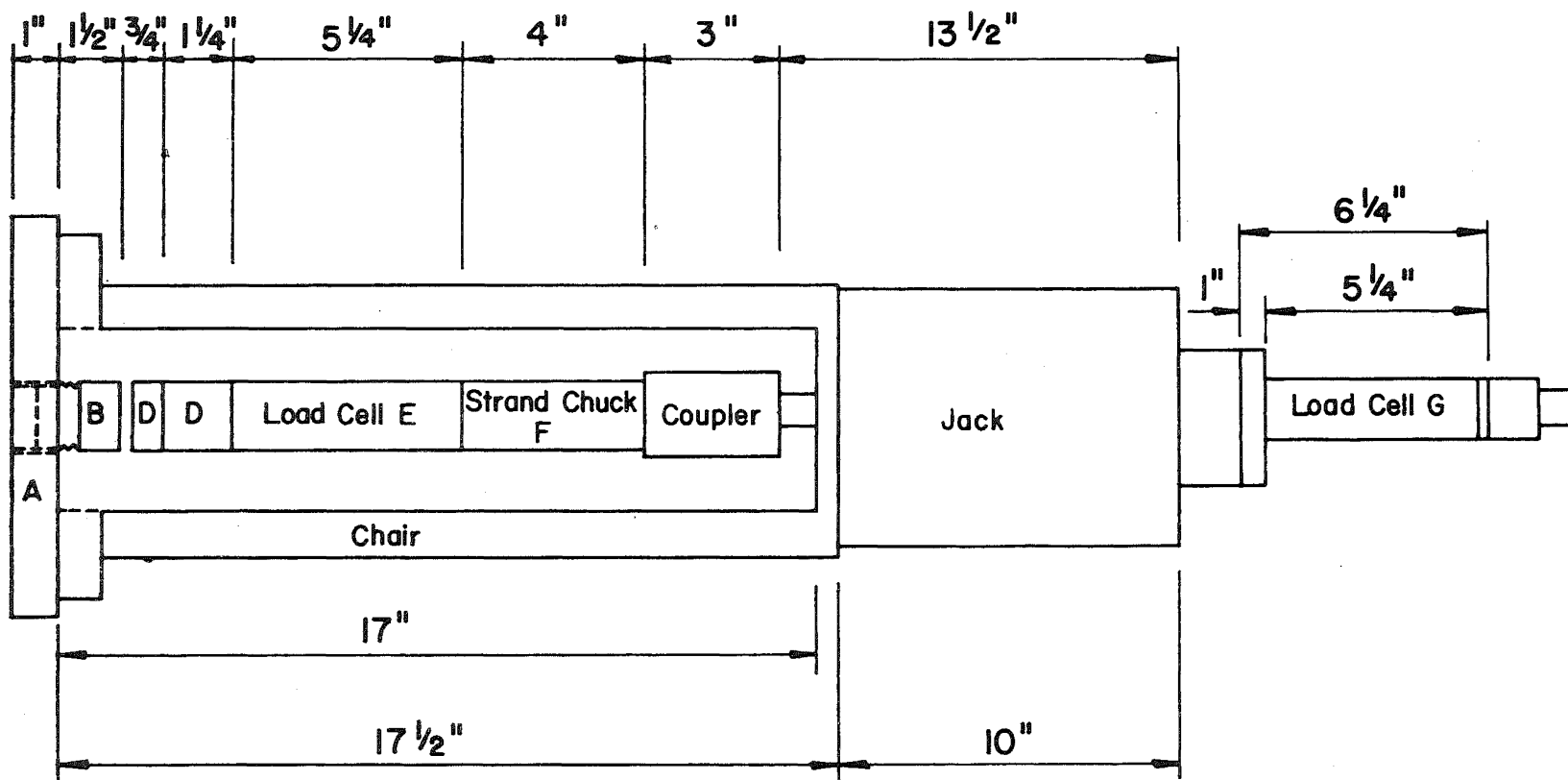


Fig. 4 Jacking and Measuring Assembly

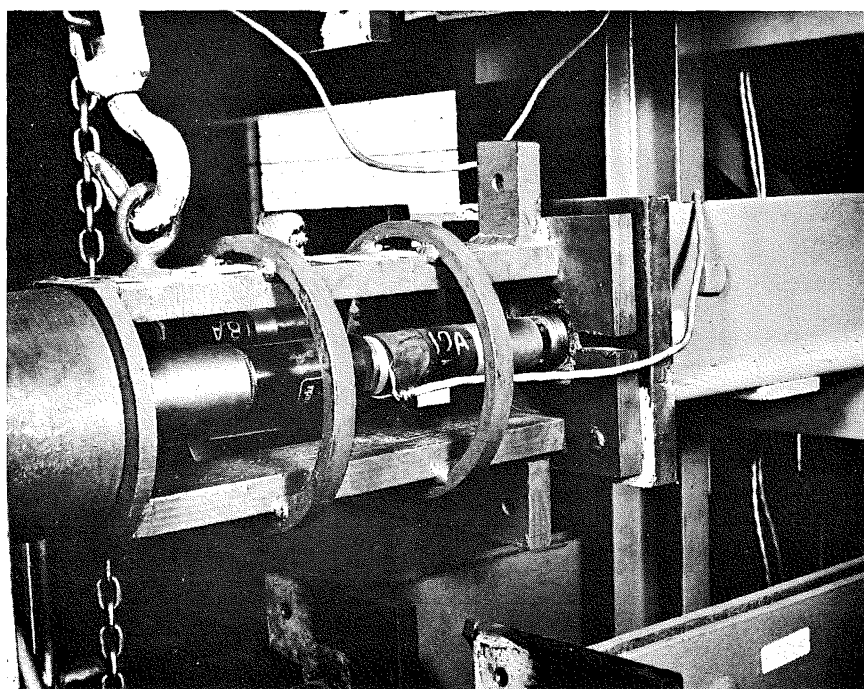


Fig. 5 Jacking End Arrangement

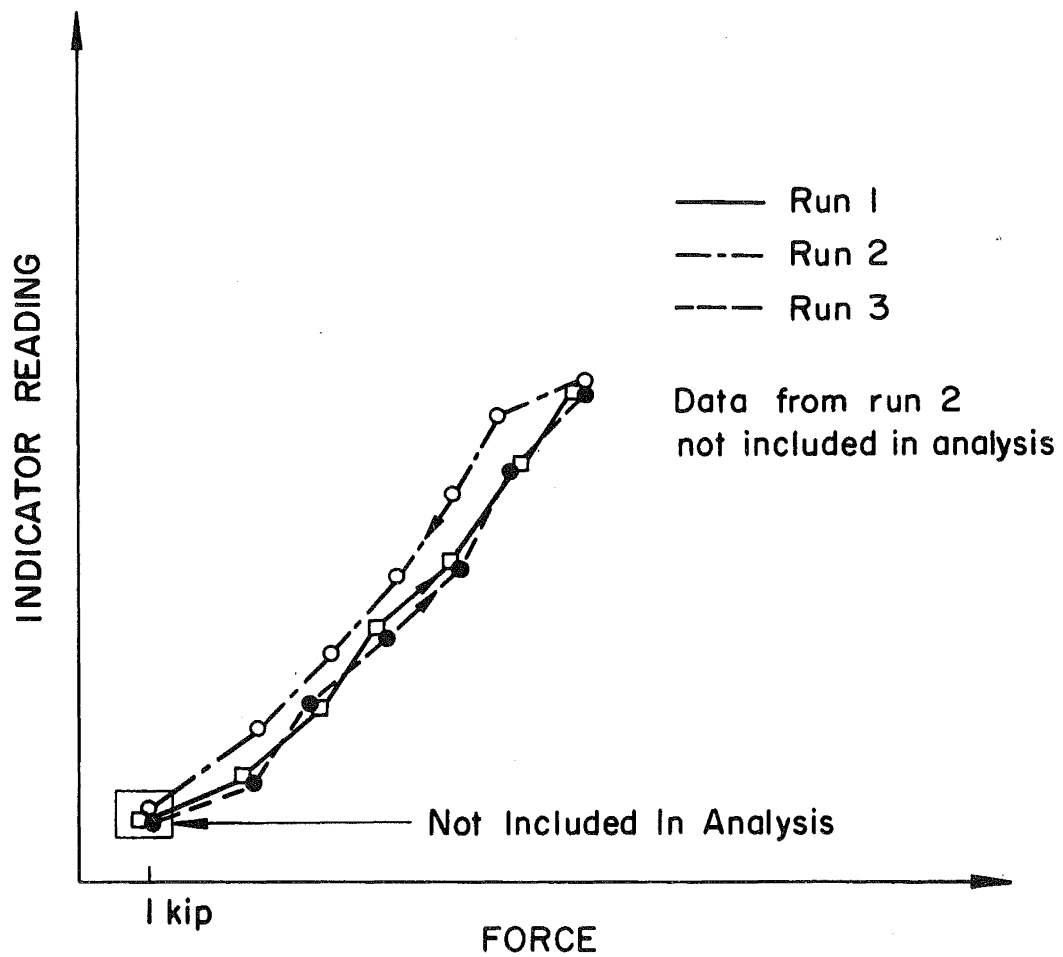
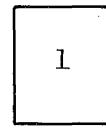
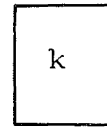
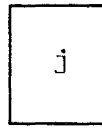
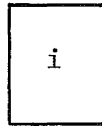


Fig. 6 Load Cell Calibration



i. DIAMETER AND TYPE OF STRAND

- A- 7/16 in. Diameter Stress Relieved
B- 1/2 in. Diameter Stress Relieved

j. MANUFACTURER

B, C, or U

k. INITIAL STRESS LEVEL

- 5- 50% f_u
6- 65% f_u
7- 70 or 75% f_u

l. NO. OF REPETITIVE SPECIMENS

1, 2, or 3

Fig. 7 Designation of Relaxation Specimens

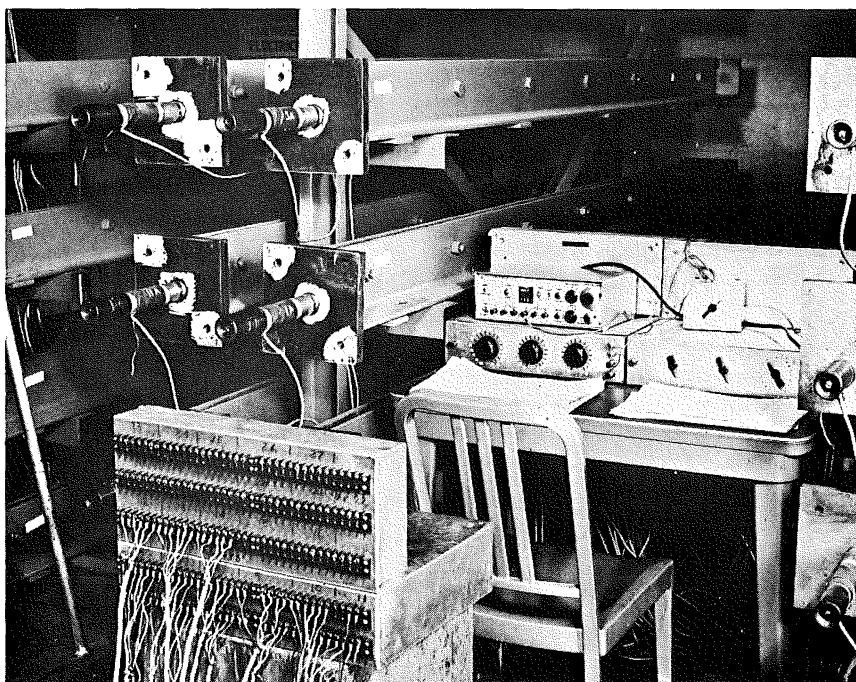


Fig. 8 Indicator Unit

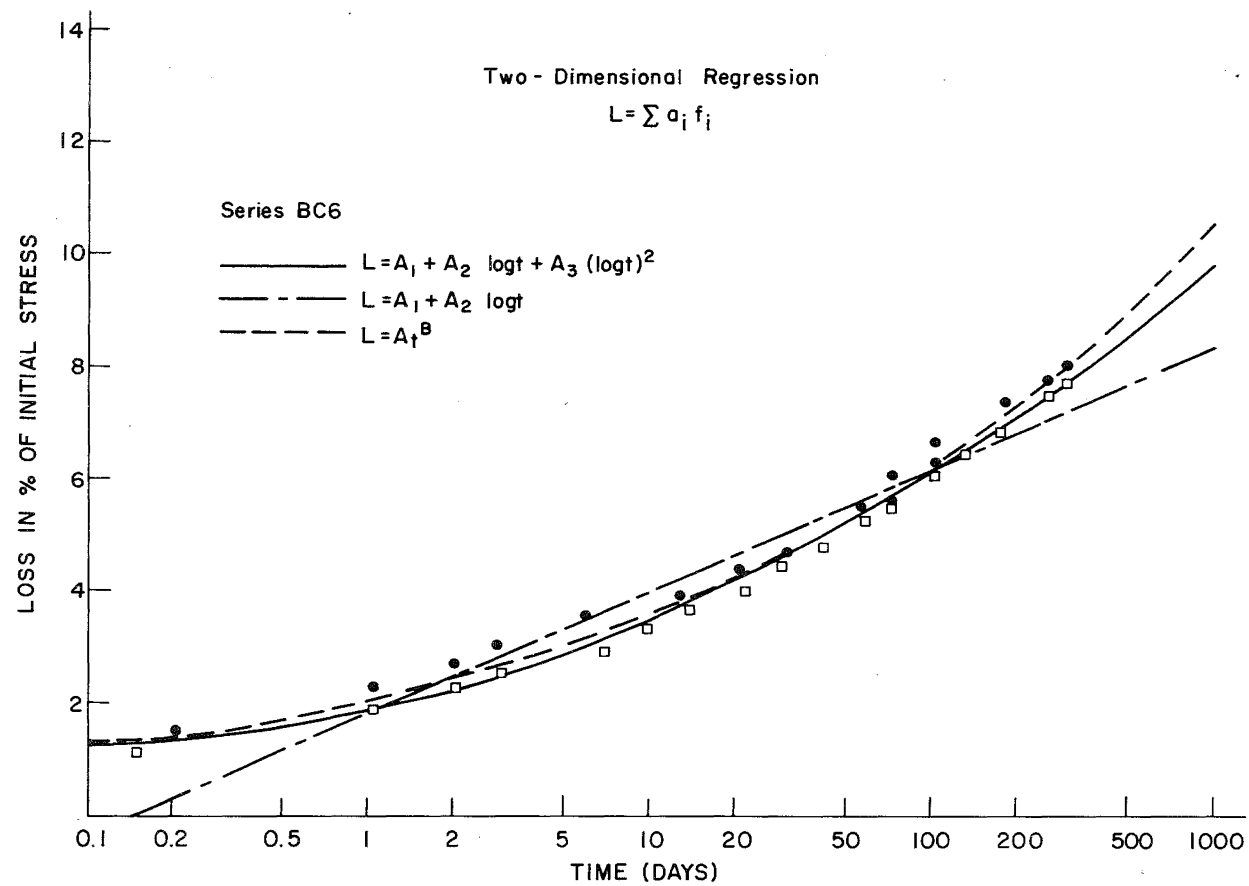


Fig. 9 Behavior of Basic Regression Time Functions

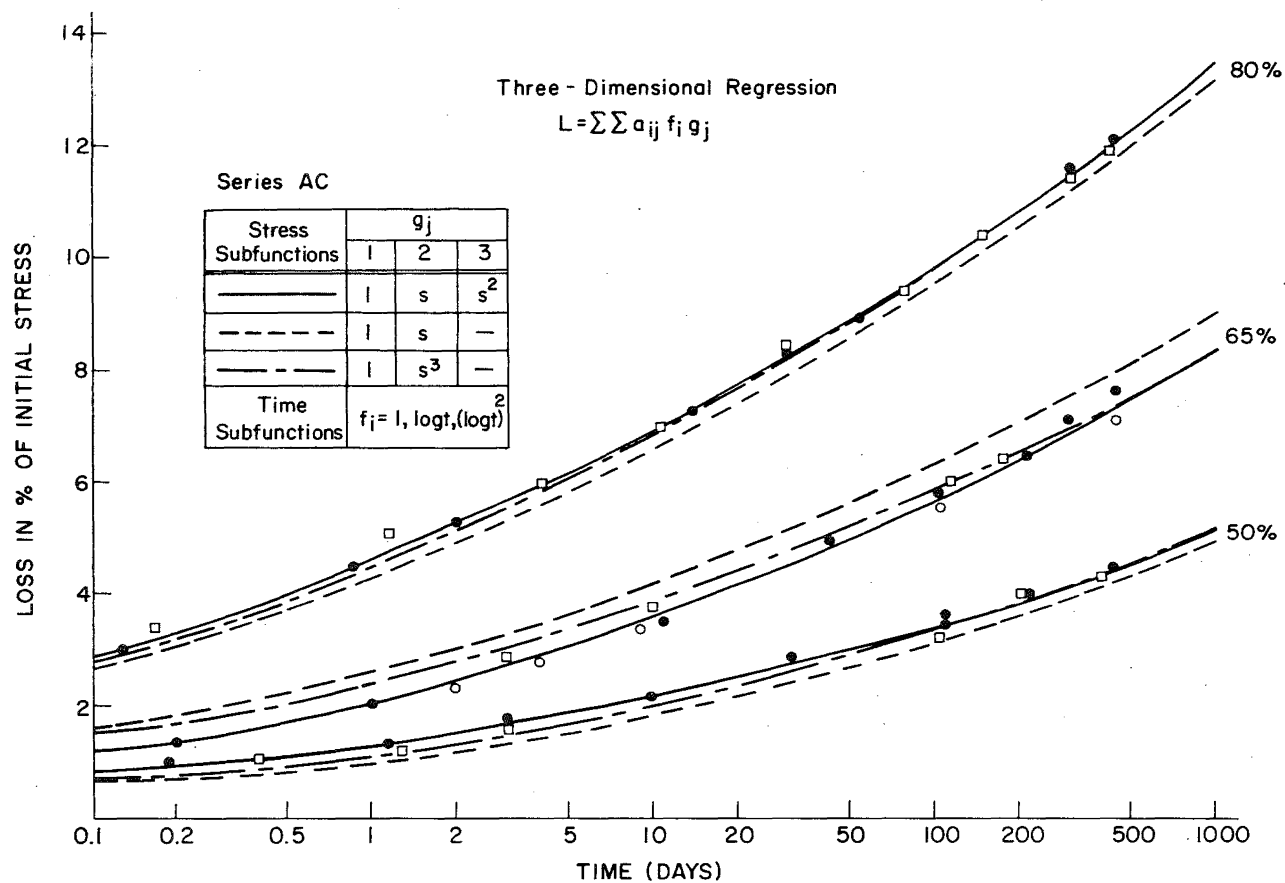


Fig. 10 Behavior of Basic Regression Stress Functions

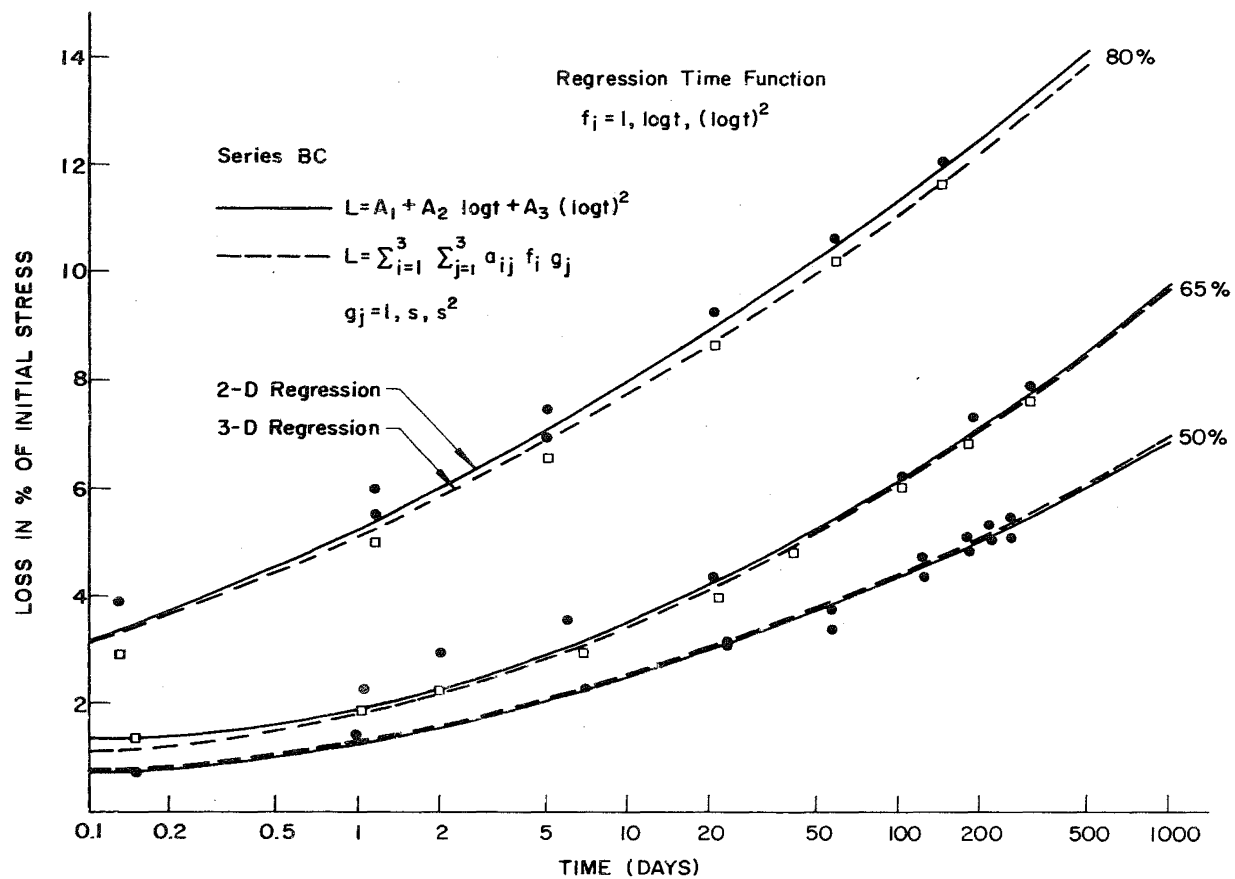


Fig. 11 Behavior of Regression Time Function $f_i = 1, \log t, (\log t)^2$

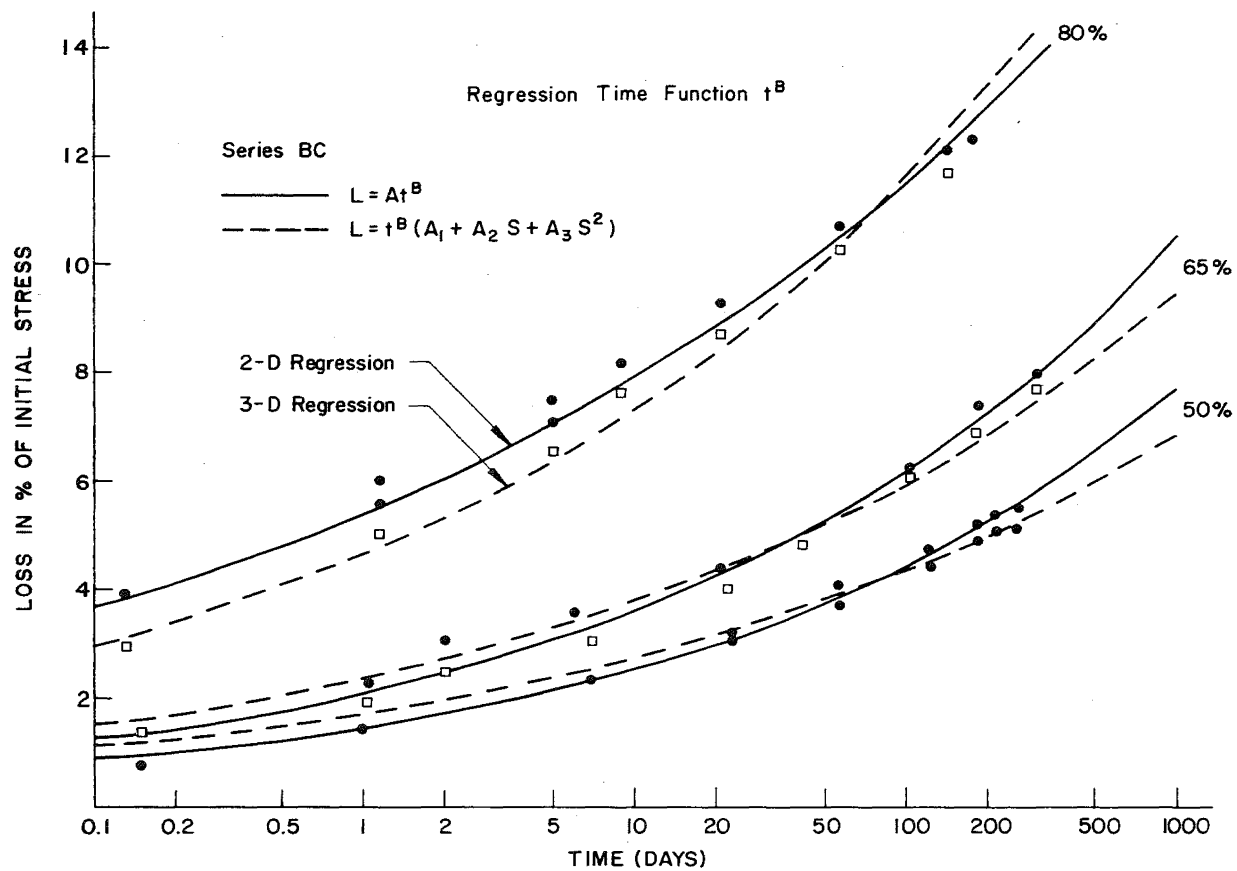


Fig. 12 Behavior of Regression Time Function t^B

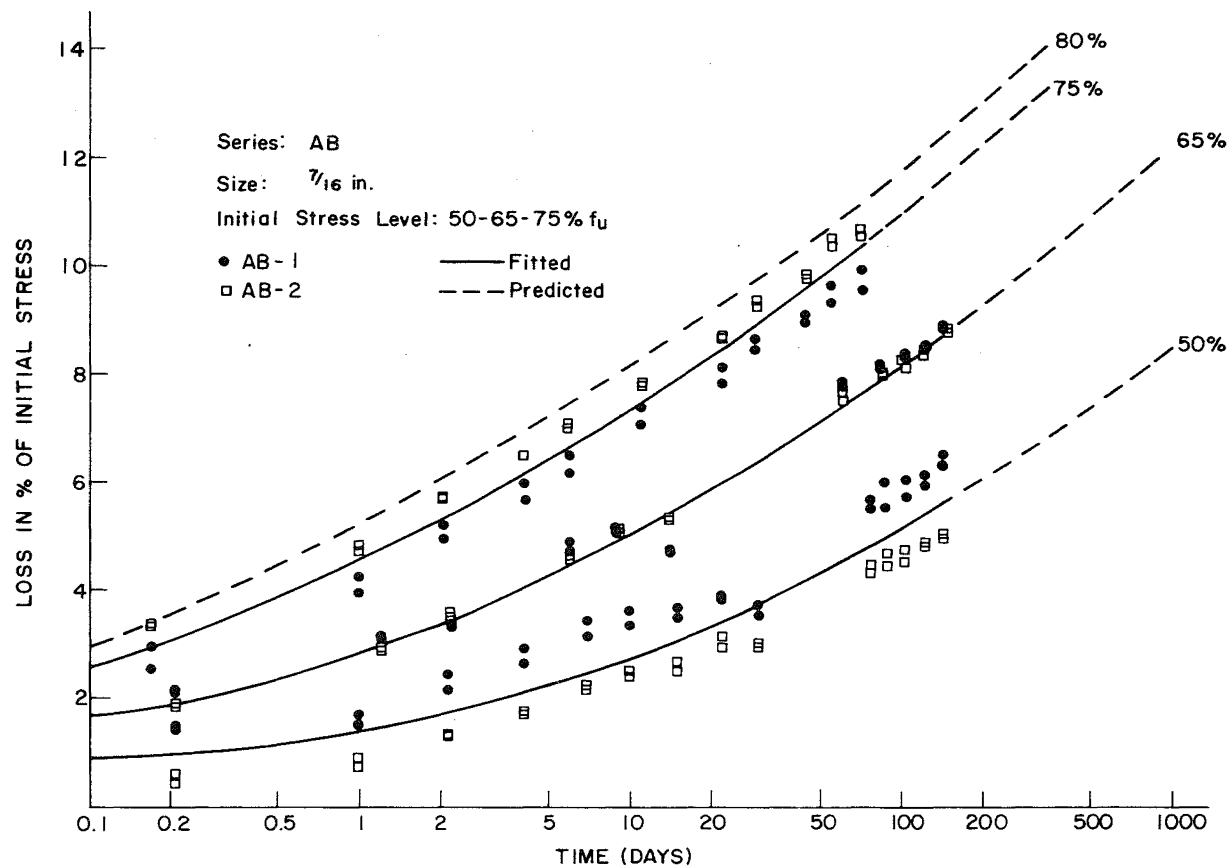


Fig. 13 Correlation of Relaxation Data Series AB

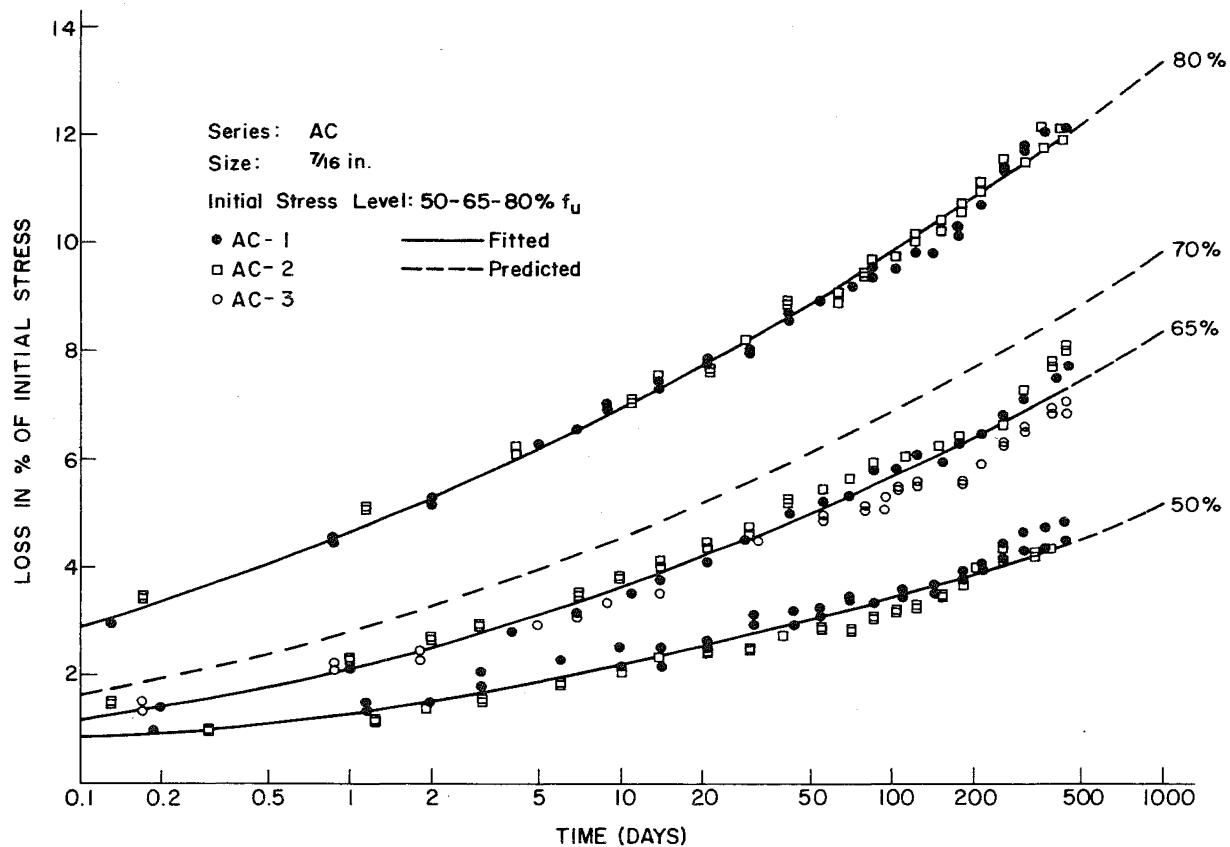


Fig. 14 Correlation of Relaxation Data Series AC

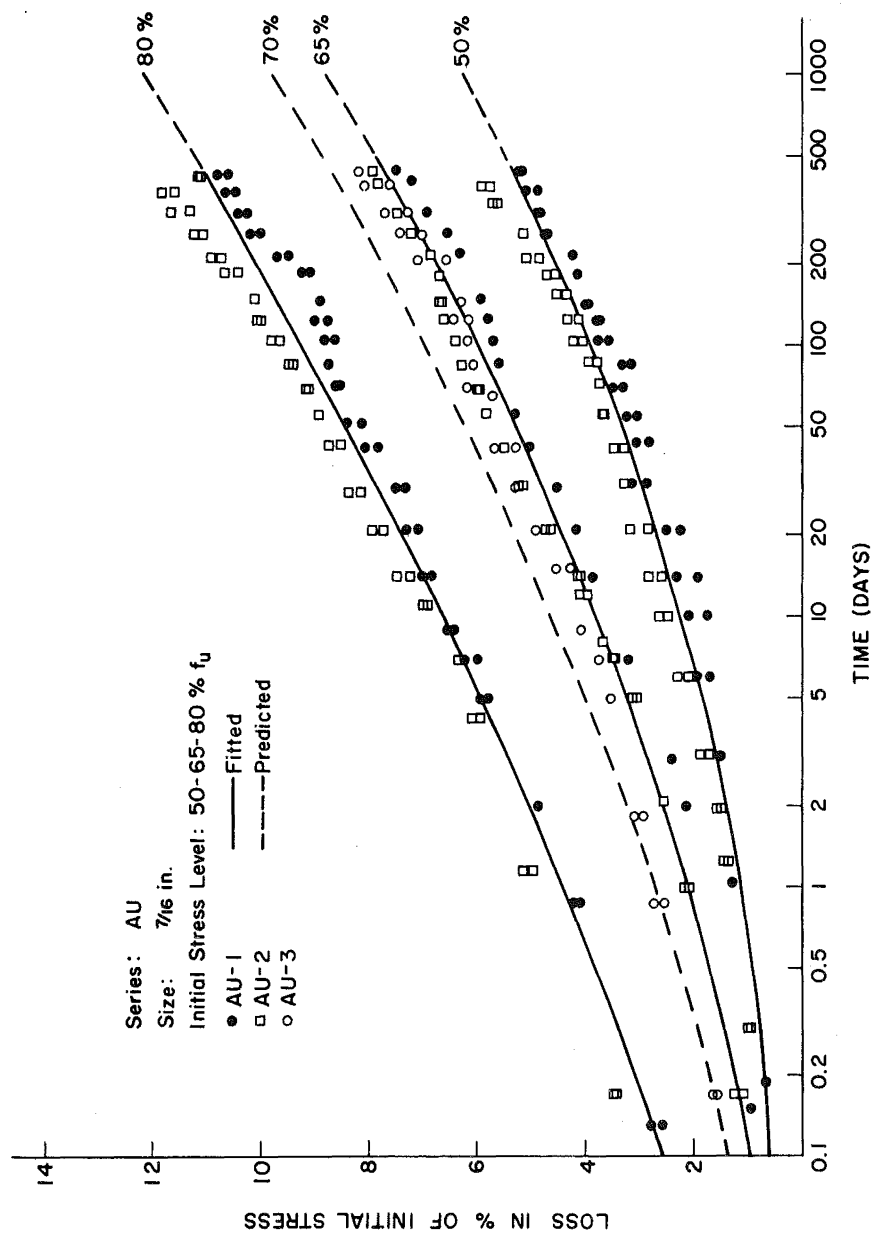


Fig. 15 Correlation of Relaxation Data Series AU

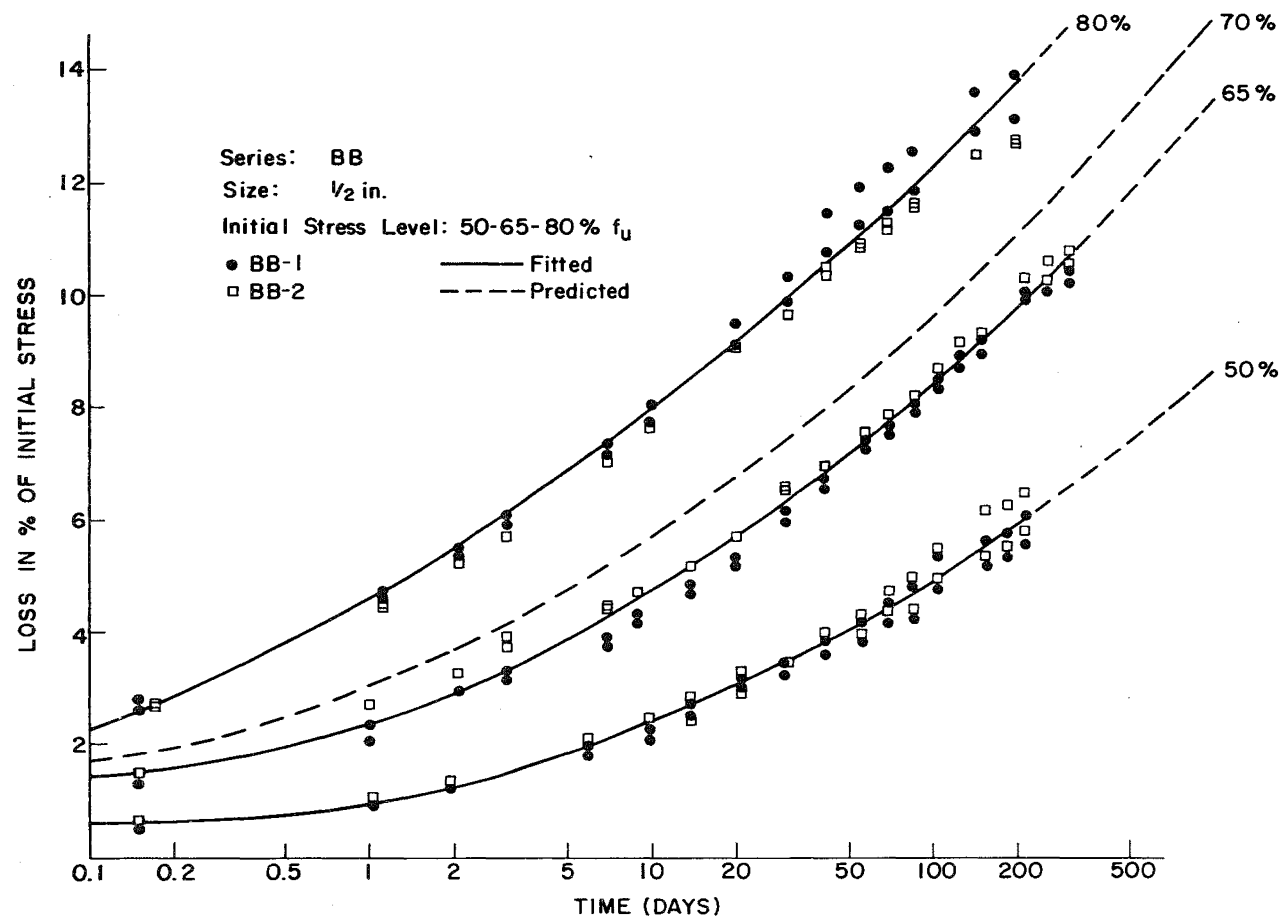


Fig. 16 Correlation of Relaxation Data Series BB

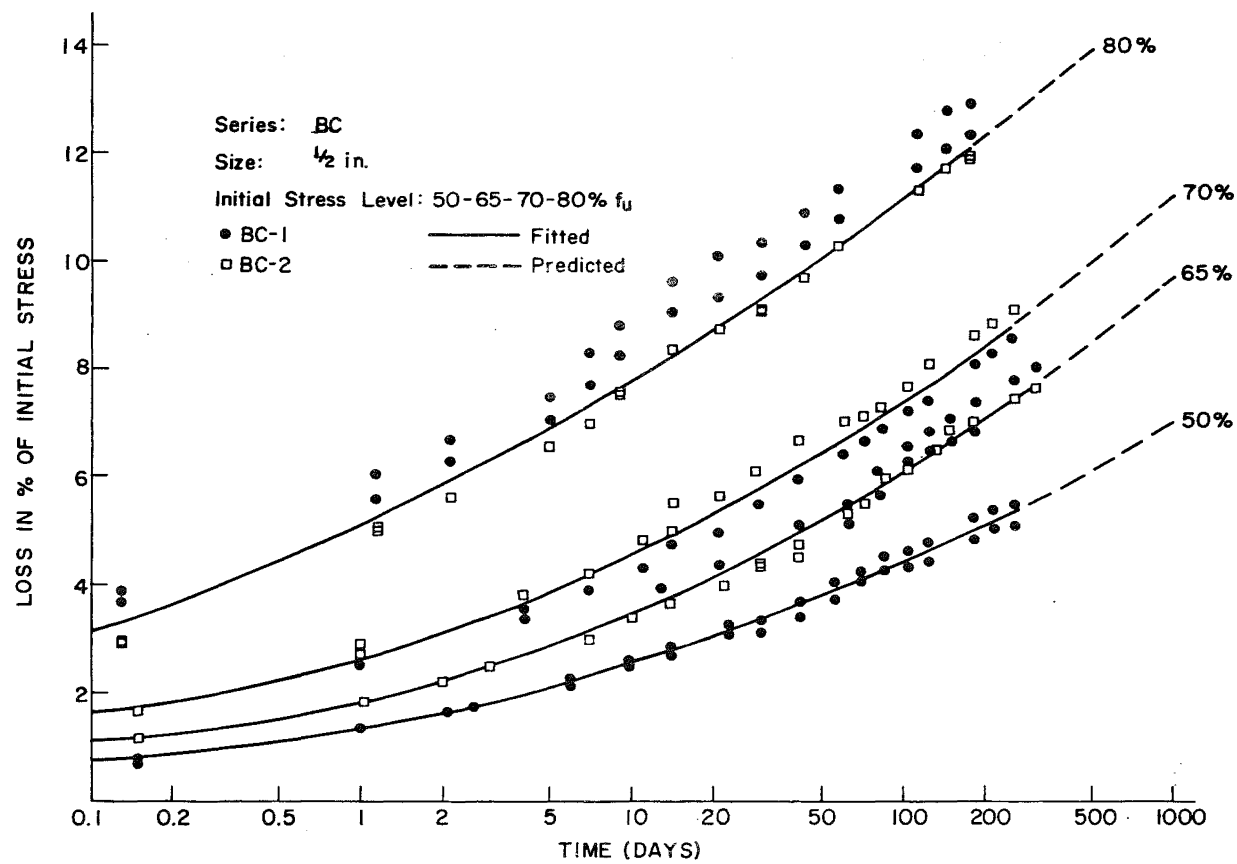


Fig. 17 Correlation of Relaxation Data Series BC

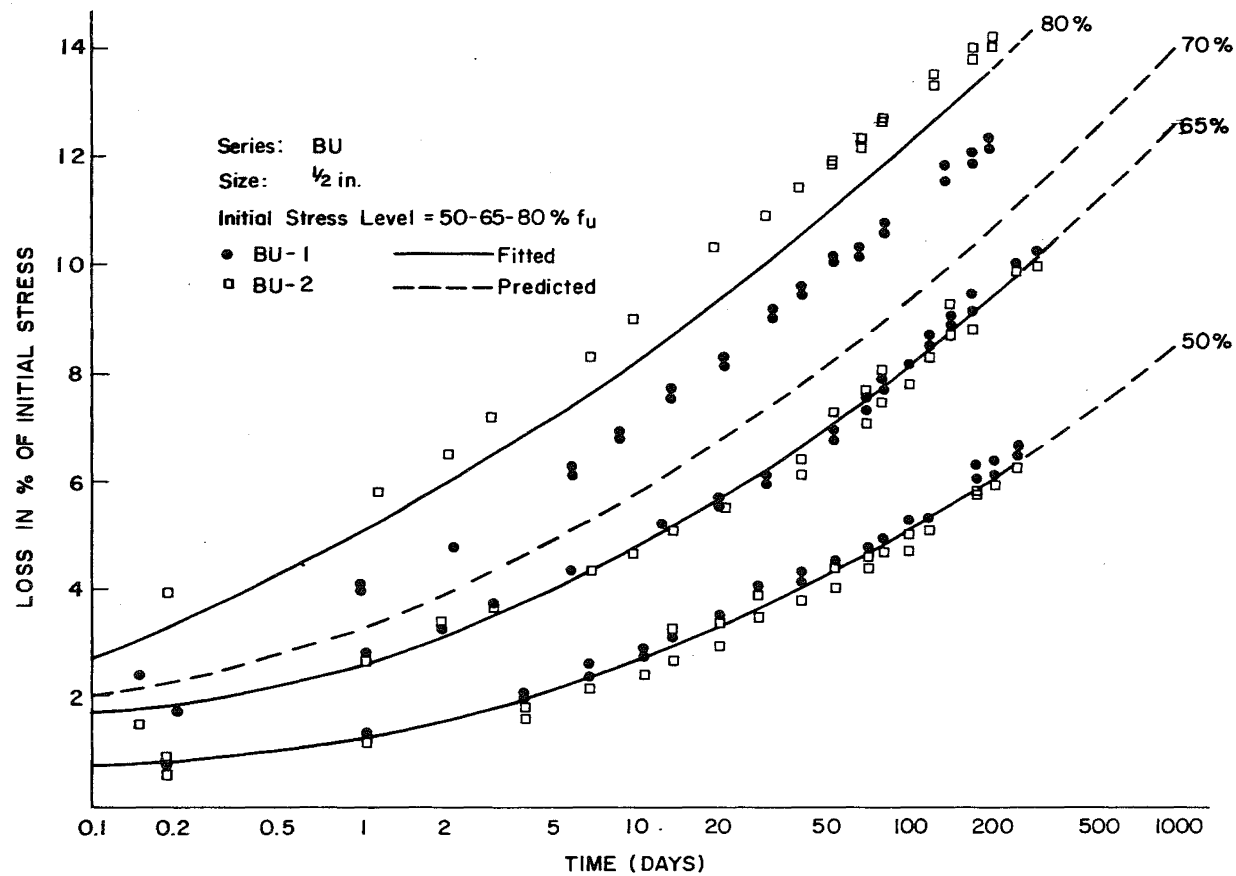


Fig. 18 Correlation of Relaxation Data Series BU

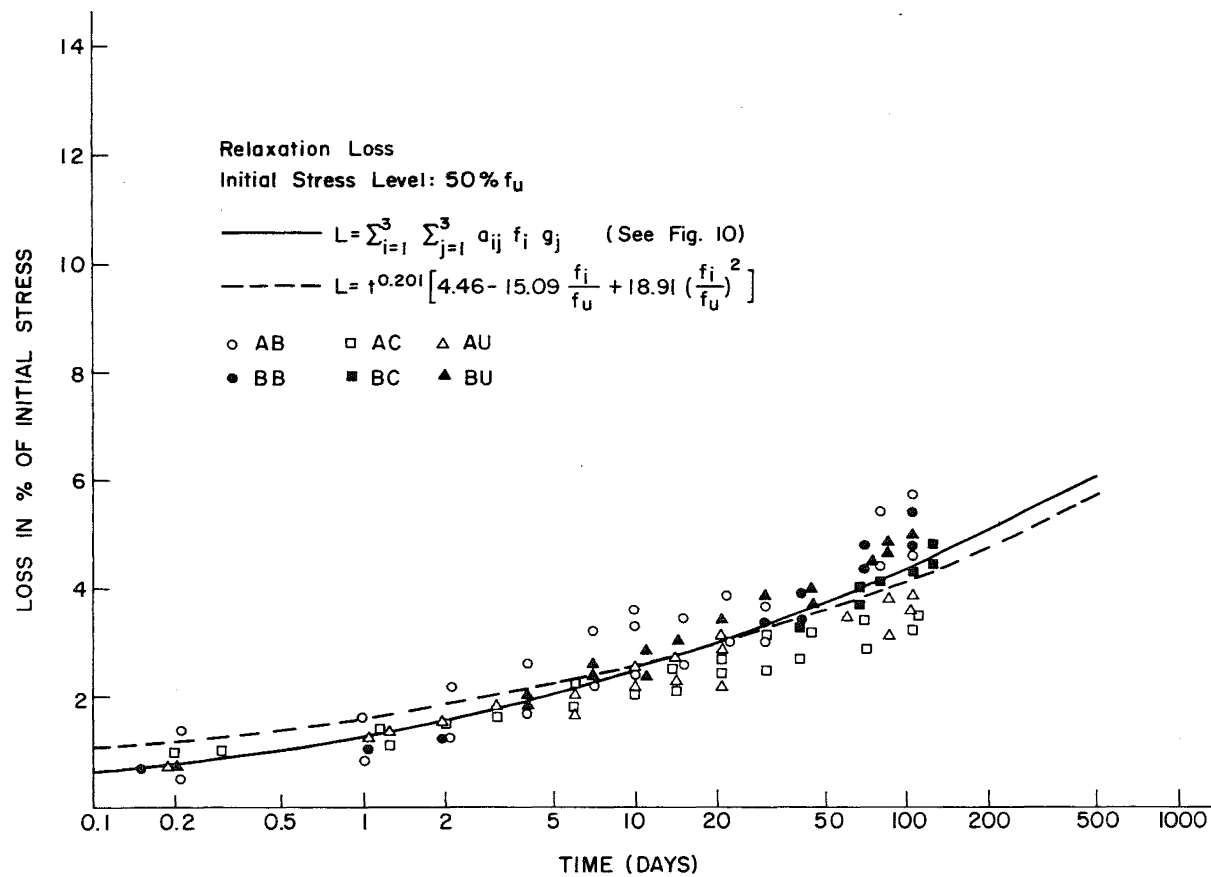


Fig. 19 Correlation of Relaxation Data All Series Combined

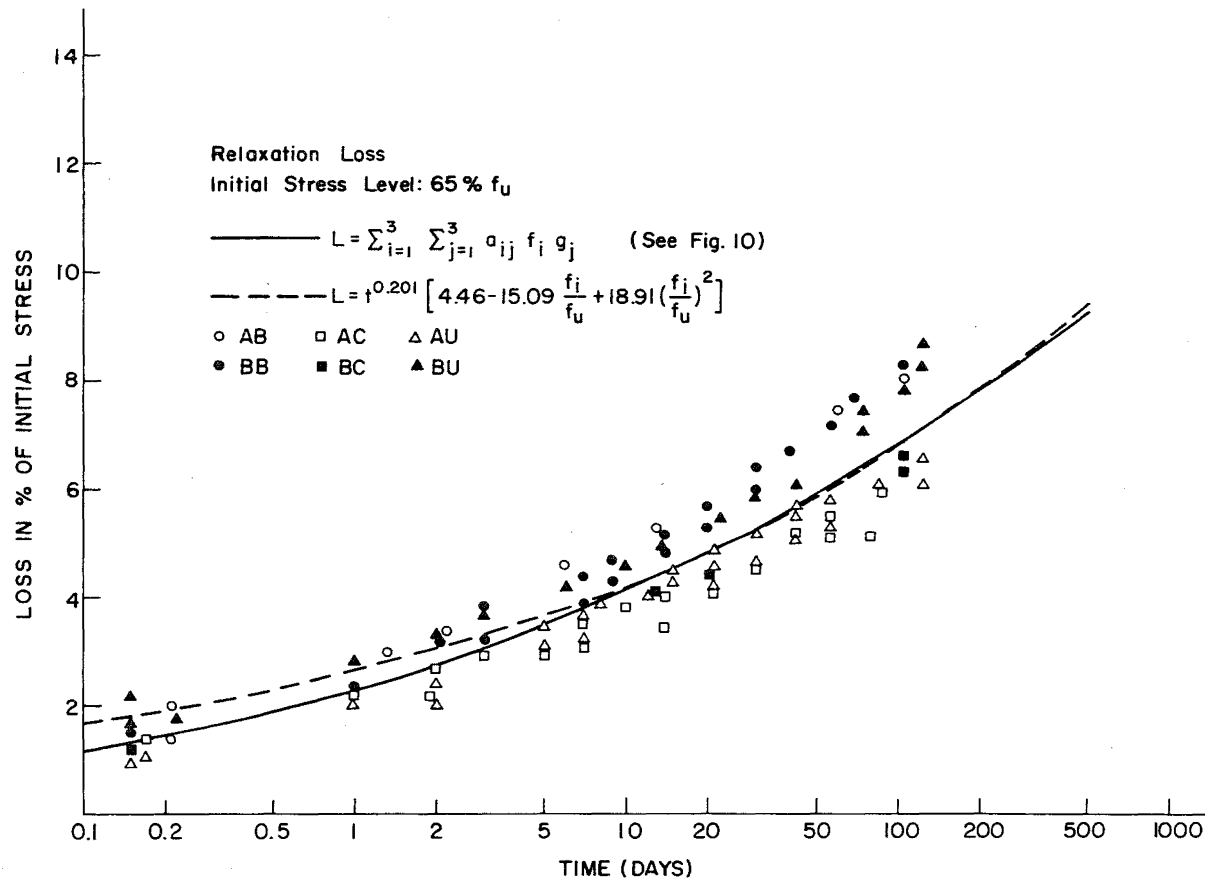


Fig. 20 Correlation of Relaxation Data All Series Combined

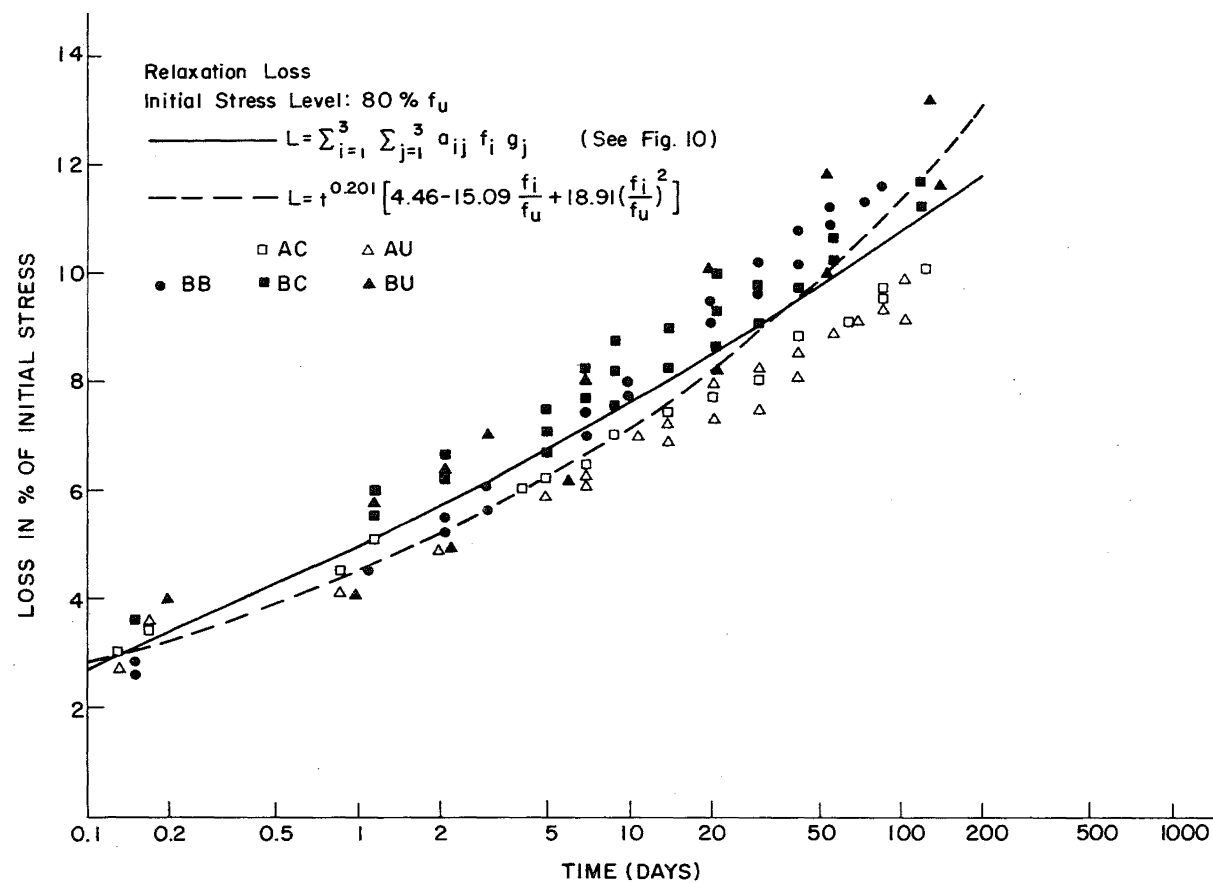


Fig. 21 Correlation of Relaxation Data All Series Combined

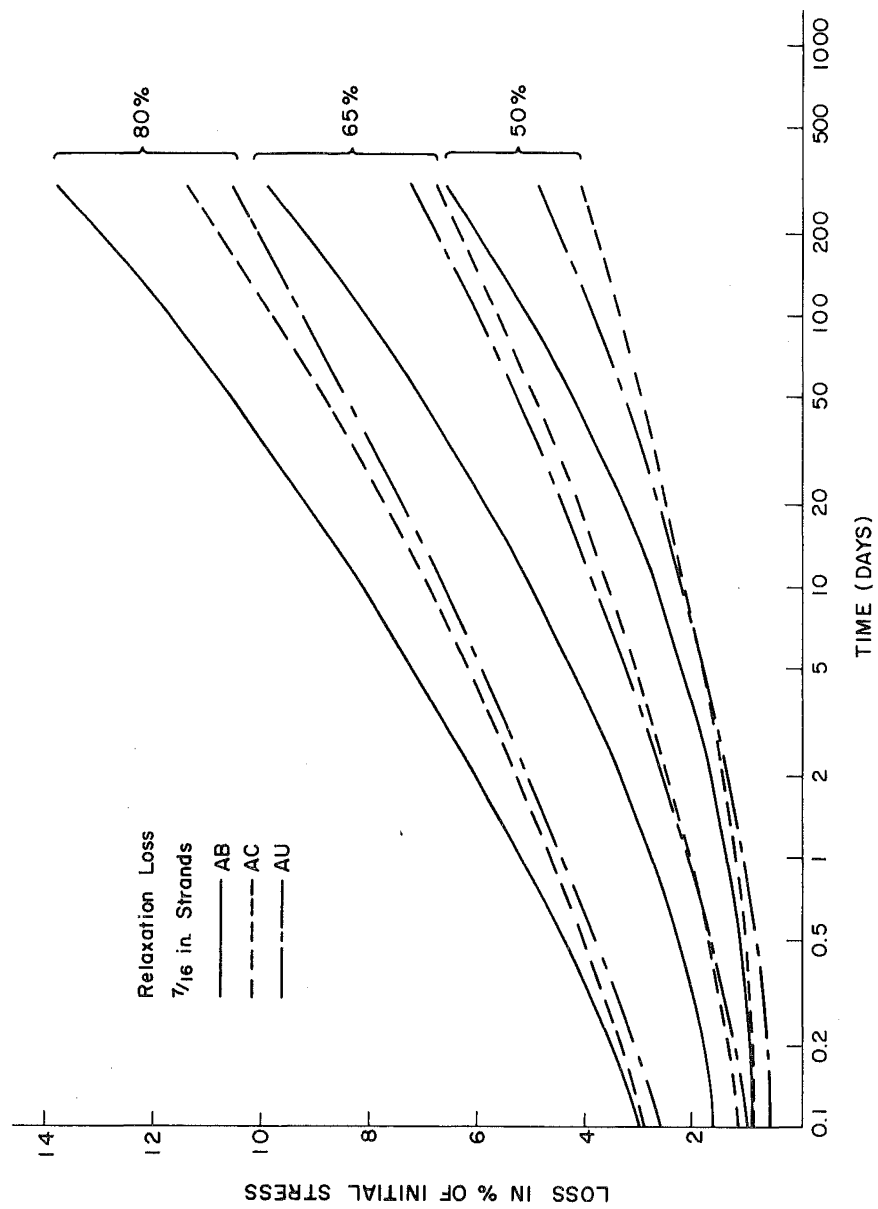


Fig. 22 Effect of Manufacturer 7/16 in. Strands

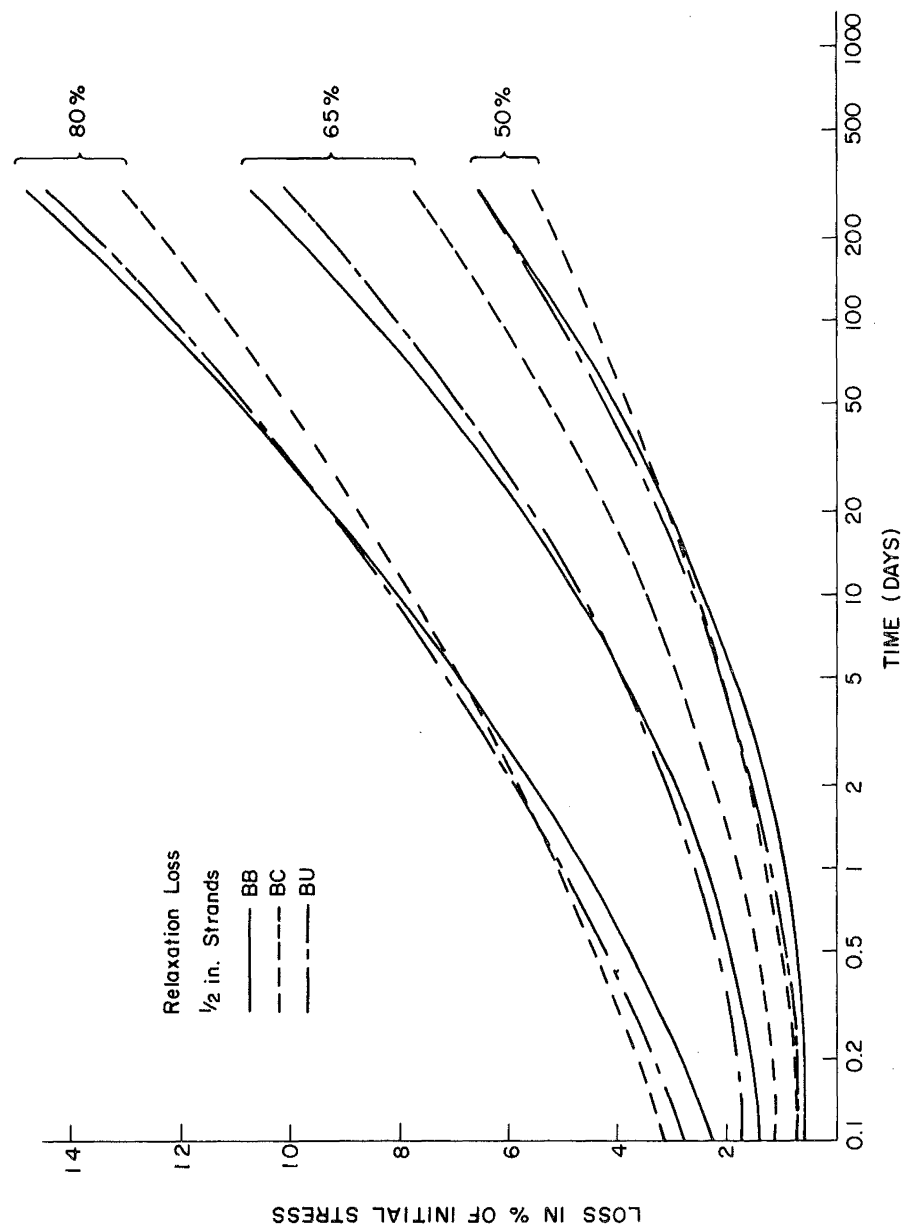


Fig. 23 Effect of Manufacturer 1/2 in. Strands

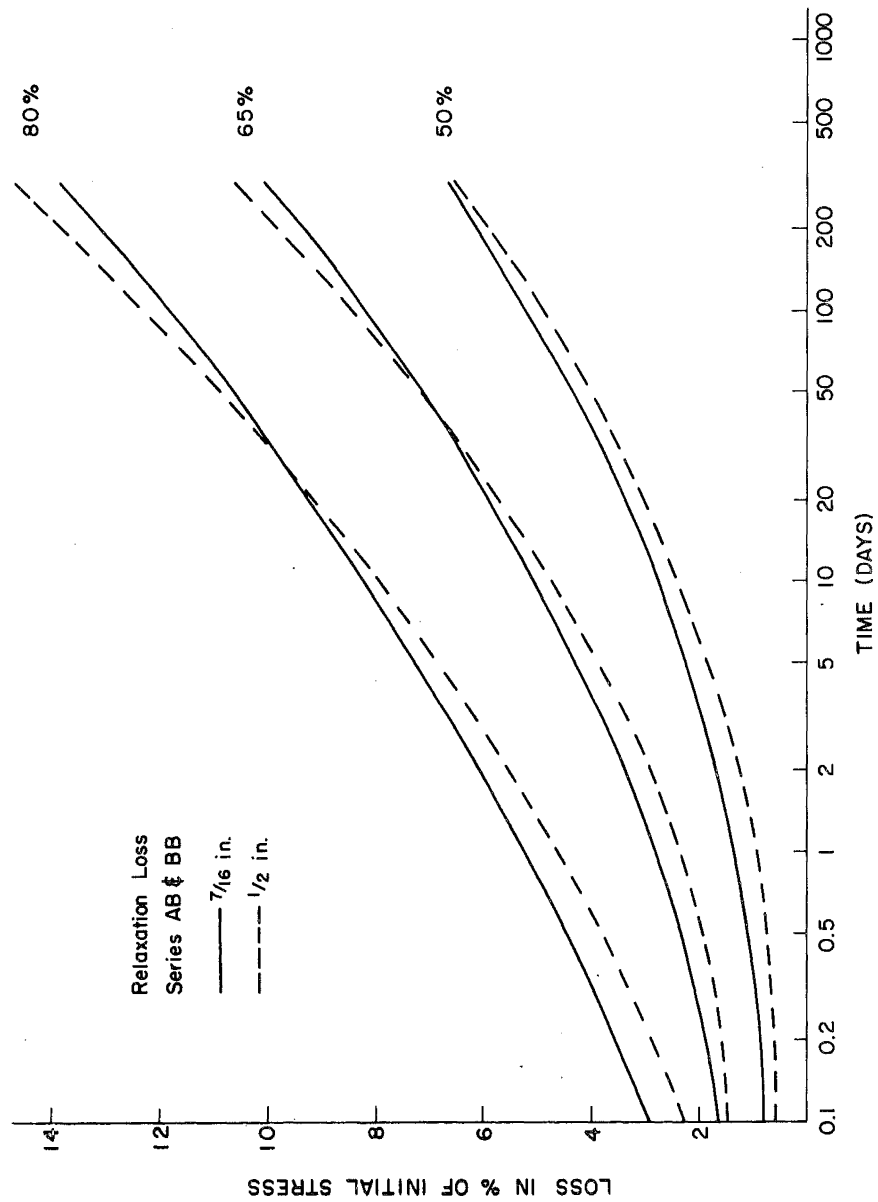


Fig. 24 Effect of Strand Size Series AB & BB

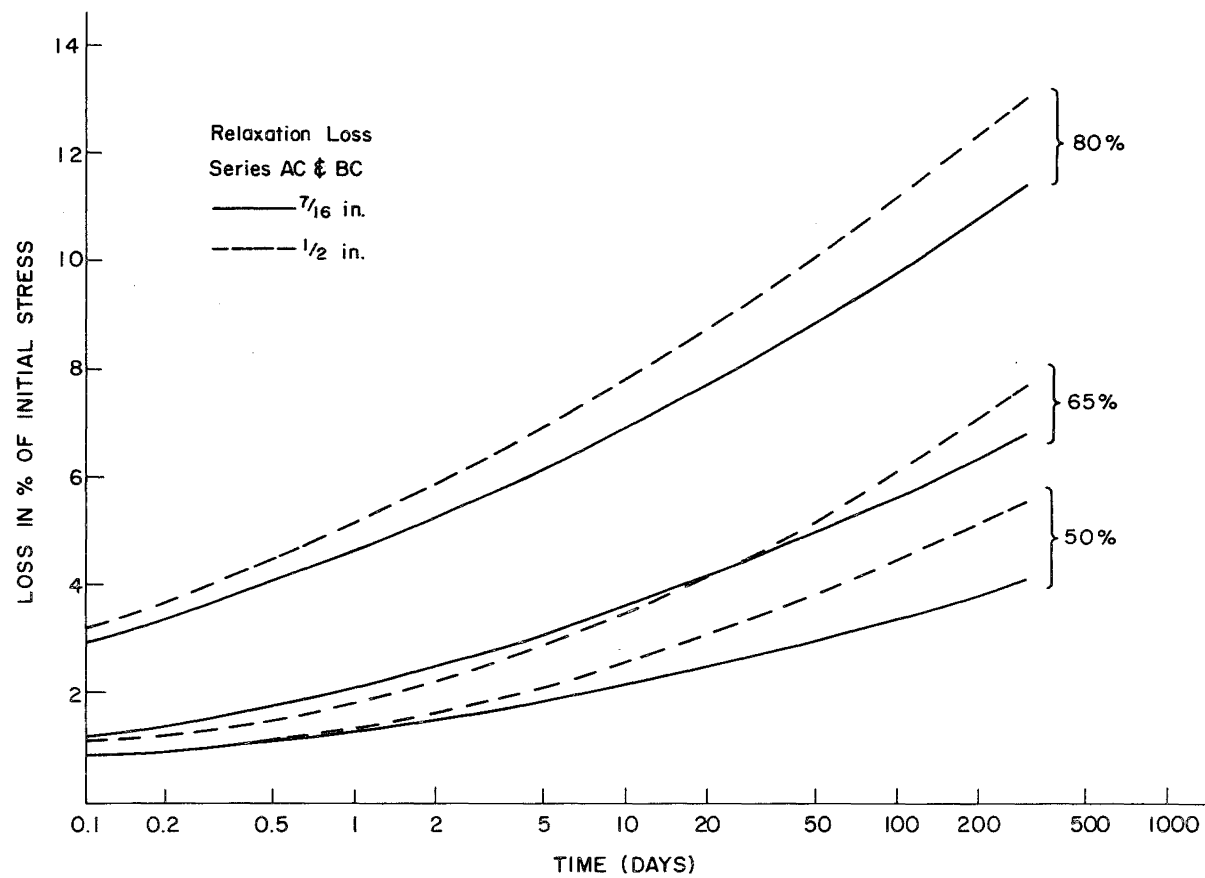


Fig. 25 Effect of Strand Size Series AC & BC

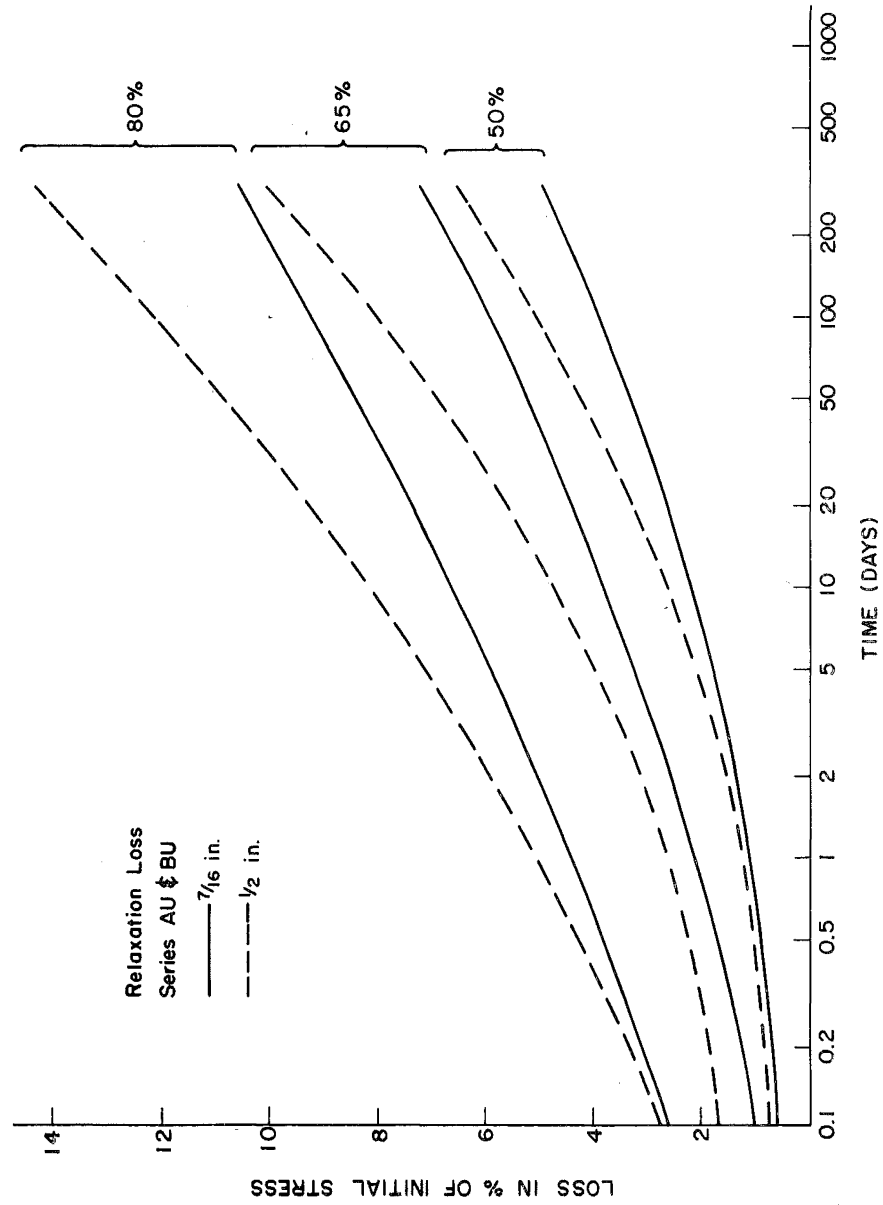


Fig. 26 Effect of Strand Size Series AU & BU

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APPENDICES

1. Strand Information
2. Computer Program SRELAB
3. Comments on Tensile Tests of Strands

Appendix 1 Strand Information

STRAND INFORMATION AS PROVIDED BY MANUFACTURER

7-Wire Stress-Relieved Strands

Special Grade (270 k)

<u>Manufacturer</u>	<u>Nom. Diam.[in.]</u>	<u>Nom. Area[in.²]</u>	<u>Ultimate Load[kip]</u>	<u>Load at 1% Extension</u>
B		0.115	----	----
C	7/16	0.117	32.820	28.500
U		0.115	35.800	30.000

Guaranteed Ultimate Load = 31.000 kip

Minimum Load at 1% Extension = 26.350

Minimum Elongation at rupture = 3-1/2 in. in 24"

B		0.156	42.540	38.500
C	1/2	0.153	42.710	37.800
U		0.1535	42.500	37.500

Guaranteed Ultimate Load = 41.300 kip

Minimum Load at 1% Extension = 35.100

Minimum Elongation at rupture = 3-1/2 in. in 24"

STRAND TEST RESULTS

ULTIMATE LOAD

<u>Strand Size</u>	<u>Manufacturer</u>	<u>Ultimate Load (kip)</u>	
		<u>I*</u>	<u>II**</u>
7/16 in.	B	32.100	32.125
	C	32.800	32.625
	U	35.575	35.000

Guaranteed Ultimate Load = 31.0 kip

1/2 in.	B	42.350	42.600
	C	42.575	42.000
	U	42.575	42.250

Guaranteed Ultimate Load = 41.3 kip

* Tested at Lehigh University

** Tested by the Pennsylvania Department of Highways

MODULUS OF ELASTICITY - E_s^*

<u>Manufacturer</u>	<u>Strand Size</u>	<u>E_s (ksi)</u>
B		29030
C	7/16 in.	29440
U		29870
B		28830
C	1/2 in.	30750
U		29210

Values Suggested by Manufacturer

B	$E_s = 28000$ ksi
C	$E_s = 28000$ ksi
U	$E_s = 28200$ ksi

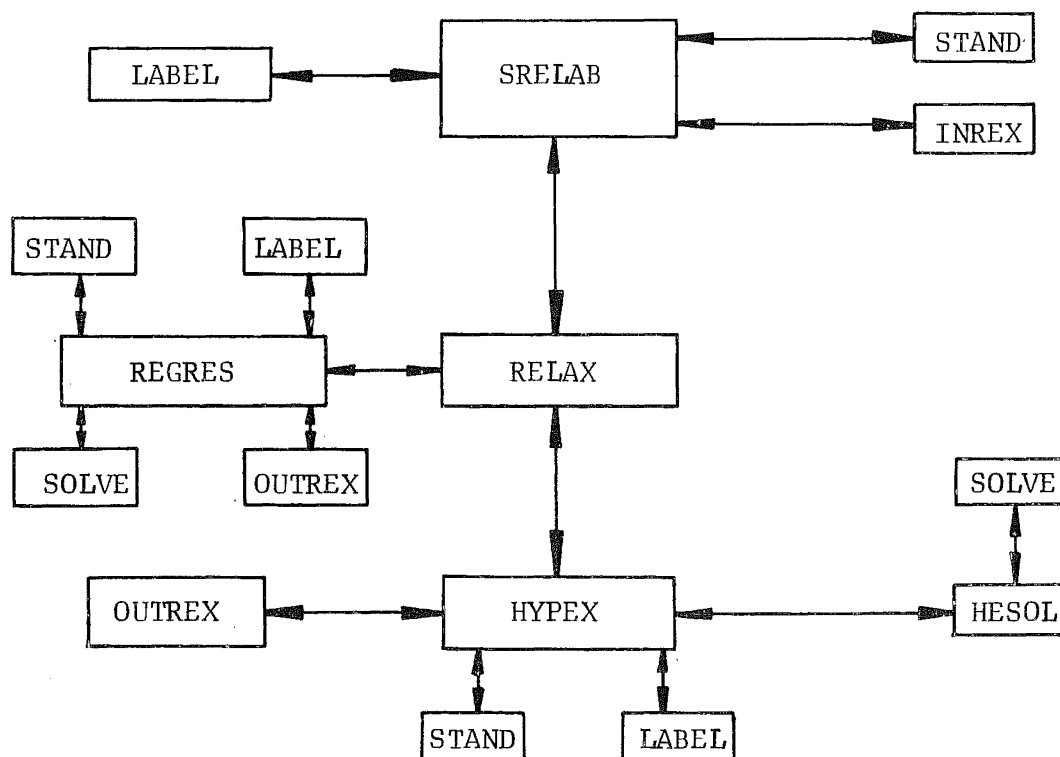
Note: Modulus of elasticity is defined here as the ratio of average stress in strand to the nominal strain in the longitudinal direction. The values listed above represent arithmetic averages of from 42 to 48 determinations, based on a gage length of 24 in., load increments of 3 kips, and taken over a range of stress up to approximately 2/3 of the ultimate strength.

* Tested at Lehigh University

Appendix 2 Computer Program SRELAB

Purpose: Regression analysis of relaxation test data, using linear, hyperbolic, or exponential time functions; Analysis for series of specimens from same manufacturer, taking into account different initial stress levels.

Chart of Main Program and Subroutines



Description

1. PROGRAM SRELAB:

Main program for three-dimensional regression of
relaxation test data

2. SUBROUTINE INREX:

Input of relaxation test data

3. SUBROUTINE OUTREX:

Output of relaxation test data

4. SUBROUTINE RELAX:

Subprogram for calling of subroutines

5. SUBROUTINE STAND:

Subprogram for estimating fitted data for standard
values of time and initial stress

6. SUBROUTINE REGRES:

Regression subprogram with linear time functions

7. SUBROUTINE HYPEX:

Regression subprogram with hyperbolic, or exponential
time functions

8. SUBROUTINE HESOL:

Iterative solution of non-linear simultaneous
equations

9. SUBROUTINE SOLVE:

Solution of system of simultaneous equations by
Gauss Elimination Method

10. SUBROUTINE LABEL:

Print of regression function

Time Subfunctions (F_i)

1, t, t^2 , t^3 , t^4 , log t, $(\log t)^2$, \sqrt{t} , e^{-t} , $\frac{1}{t}$

Stress Subfunctions (G_i)

1, s, s^2 , s^3 where $s = \frac{f_i}{f_u}$

Appendix 3 Comments on Tensile Tests of Strands

In Chapter 3, it was noted that two 7/16 in. diameter specimens from manufacturer B failed before reaching a desired initial stress of 80% of the guaranteed ultimate tensile strength, and that their replacements were tested at a slightly lower 75% stress level. It is appropriate to include additional comments to prevent any implication on the suitability of the sample materials.

First of all, it should be pointed out that stress concentration always develops in a test specimen wherever the cross-section changes abruptly. When a seven wire strand is gripped with standard strandvises and placed under tension, the teeth of the grip will cut into the wires, forming an abrupt change leading to stress concentration. Failure will always take place at these indentations, in a brittle manner, before the full strength of the strand could be realized. In order to avoid such premature failures, tensile strength tests for strands are performed using special anchorage devices. The tests at Lehigh University, with results reported in Appendix 1, were conducted using a pair of copper bars squeezed between the strand specimen and the standard V grips of the testing machine. Most of the tensile load in the specimen is transmitted through friction, causing little or no stress concentration. Tested with this special arrangement, all strands failed outside of the gripped region, with significant plastic deformation. It can be seen from Appendix 1 that all

strands meet the required guaranteed ultimate strength with varying amount of margin. In particular, the 7/16" manufacturer B strands tested more than 3% higher than the guaranteed strength.

Tensile strength tests were also conducted using standard strandvises as the holding device, after the two aforementioned strands failed prematurely in the stretching process. All strands, including both sizes and all three manufacturers, failed inside of the grips at significantly lower loads. The ratio of the failure load obtained in this manner to the guaranteed ultimate load varied from 87 to 97%, except for the 7/16 in. manufacturer B strands, which failed at 78 to 85% load. It is apparent that this particular strand is much more strongly susceptible to the stress concentration problem than all others. However, it appears to have met all the mechanical requirements for prestressing strands, and should be accepted.

With the above background information, the premature failure of the two 7/16 in. manufacturer B strands should not be surprising, as standard strandvises were used on all test specimens. The replacement specimens were taken from the same lot of material supplied by the manufacturer. These were tested at a slightly lower initial stress of 75% ultimate load, in order to avoid similar premature failures. It should be pointed out that the high initial stress level was intended to provide a practical upper bound of strand stress, as well as to reveal any non-linearity between relaxation loss and initial stress. Both purposes could be fulfilled by tests at 75% initial stress level.